Cognitive Radio from a Mobile Operator's Perspective: System Performance and Business Case Evaluations

by

Pål R. Grønsund

Doctoral Dissertation submitted to
the Faculty of Mathematics and Natural Sciences
at the University of Oslo
in partial fulfilment of the requirements for
the degree of Philosophiae Doctor

June 2013

Abstract

Cognitive Radio (CR) is a promising technology to solve the spectrum scarcity problem and to increase spectrum efficiency. By using spectrum sensing and databases, one is able to obtain information about and utilize white space spectrum. Spectrum costs, which tend to be high for mobile operators, can then be reduced significantly. For mobile operators, CR technology brings threats and opportunities. Two evident threats are the risk of increased interference and competition when secondary users access white spaces in the operator's own spectrum. Considering the high level of activities on CR in research, standardization and regulation in addition to commercial activities, CR might eventually emerge in the telecommunications market. Therefore, instead of focusing on the threats only, mobile operators should focus on understanding how they can benefit from using CR. One opportunity is to use CR to get access to more spectrum to cope with the increasing wireless data demand and spectrum scarcity. Another opportunity is to use CR to access spectrum in, and to enter, new markets where there are no available spectrum licenses.

The objective of this thesis is to study and understand how a mobile operator can benefit from using CR as a potential sustaining or disruptive innovation to opportunistically access white spaces. We show, by example case studies, that there are potentials for a mobile operator to use CR to access white spaces and achieve well performing technical and economic viable solutions. In particular, we study three important areas for CR with focus on the mobile operator's perspective.

First, we characterize spectrum usage and analyze potential capacity for CR access in primary OFDMA networks. We show that there is a potential for CR systems to utilize white spaces. Furthermore, we propose that cooperation with the primary operator is important to maximize spectrum utilization.

Second, we study the concept of a sensor network aided CR system. We propose three business cases and evaluate the economic viability. The most promising business case for an operator is that of a joint venture that gets the rights to use the "unused" spectrum resources of spectrum owners. We find that high reuse of existing base station sites by the CR system is a business critical parameter. Furthermore, it is found challenging to achieve high reuse of existing base station sites when evaluating technical performance using a simulation model. Hence, this points in the direction of shorter range and less expensive access points such as femtocells. However, we show that full reuse of base station sites

can be achieved by relaxing interference requirements for the CR. Then, we propose a promising business case that uses cognitive femtocells aided by a sensor network to offload the LTE network.

Third, we use simulations to evaluate performance of the first CR standard IEEE 802.22. We find that the activity of wireless microphones as the primary users should be quite high to reduce throughput and delay. Interference to the wireless microphone is found to be low in general and to occur only for short periods when using novel sensing strategies. Furthermore, we show that the guaranteed bit rate QoS service for VoIP can be prioritized. Though, the spectrum sensing strategy is important to satisfy strict QoS requirements for throughput and delay. Finally, we explore spectrum selection functions, which are used as basis for channel selection. We show that selection functions that utilize long-term spectrum usage statistics based on historic, accumulated sensing results can enhance over-all performance.

Preface

This Doctoral Dissertation is submitted to the Faculty of Mathematics and Natural Sciences at the University of Oslo in partial fulfilment of the requirements for the degree of Philosophiae Doctor. My main supervisor has been Professor Paal E. Engelstad from the University of Oslo, Telenor ASA and Simula Reseasrch Laboratory. My co-supervisors have been Dr. Przemysław Pawełczak from the Delft University of Technology and Dr. Audun Fosselie Hansen from Simula Research Labaratory. Researcher Ole Grøndalen from Telenor ASA has been my informal supervisor and mentor.

The research work leading to this dissertation was conducted in the period from January 2009 to June 2013. One semester has been dedicated to course work (30 credits). About 25% of the time has also been dedicated to research projects in Telenor ASA, especially in the international EU FP7 funded research projects SENDORA and QoSMOS. The dissertation has been a collaborative project with Telenor ASA, the University of Oslo and Simula Research Laboratory. Part of the work has also been conducted in cooperation with, including a three month research visit at, the Cognitive Reconfigurable Embedded Systems lab at the University of California, Los Angeles.

This research work has been supported by the Research Council of Norway under the Industrial PhD scheme for industry-oriented doctoral research fellowships and by Telenor ASA.

List of Publications

The papers included in this thesis, referred to as Papers A-I, are listed below and included in Part II of this thesis. The Papers 1-7 are related publications not included in this thesis.

Main Contributions

Paper A P. Grønsund, H.N. Pham and P.E. Engelstad, "Towards Dynamic Spectrum Access in Primary OFDMA Systems", in Proc. 20th IEEE Personal, Indoor and Mobile Radio Communications Symposium (IEEE PIMRC), Tokyo, Japan, Sep. 13-16, 2009.

Paper B O. Grøndalen, M. Lähteenoja and P. Grønsund, "Evaluation of Business Cases for a Cognitive Radio Network based on Wireless Sensor Network", in Proc. 5th IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (IEEE DySPAN), Aachen, Germany, May 3-6, 2011.

Paper C P. Grønsund and O. Grøndalen, "Comparison of Cell Sizes for Cost Efficient Deployment of a Sensor Network Aided Cognitive Radio System", Journal of Signal Processing Systems, vol. 69, no. 1, pp. 95-104, Oct. 2012.

Paper D P. Grønsund and O. Grøndalen, "Evaluation of Interference Requirements in a Sensor Aided Cognitive Radio System", in Proc. 54th IEEE Global Communications Conference (IEEE GLOBECOM), Houston, Texas, USA, Dec. 3-7, 2011.

Paper E P. Grønsund, O. Grøndalen and M. Lähteenoja, "Business Case Evaluations of LTE Network Offloading with Cognitive Femtocells", Telecommunications Policy, vol. 37, no. 2-3, pp. 140-153, Mar.-Apr. 2013.

Paper F P. Grønsund, P. Pawełczak, J. Park and D. Čabrić, "System Level Performance of IEEE 802.22 with Sensing-Based Detection of Wireless Microphones", Accepted for publication in IEEE Communications Magazine, 2013.

Paper G P. Grønsund, P. Pawełczak, J. Park and D. Čabrić, "Sensing of Wireless Microphones in IEEE 802.22: A System Level Performance Evaluation", IEEE International Conference on Communications (IEEE ICC), Budapest, Hungary, Jun. 9-13, 2013.

Paper H J. Park, P. Pawełczak, P. Grønsund and D. Čabrić, "Analysis Framework for Opportunistic Spectrum OFDMA and its Application to IEEE 802.22 Standard", IEEE Transactions on Vehicular Technology, vol. 61, no. 5, pp. 2271-2293, Jun. 2012.

Paper I P. Grønsund, P.E. Engelstad, P. Pawełczak, O. Grøndalen, P.H. Lehne and D. Čabrić, "Spectrum Sensing Aided Long-Term Spectrum Management in Cognitive Radio Networks", Submitted to IEEE Conference on Local Computer Networks (LCN), Sydney, Australia, Oct. 21-24, 2013.

Other Publications

In Paper 1, an implementation and evaluation of ideas presented in Paper A is given. Papers 2-3 are related to papers B-E. Papers 4-5 are related to papers F-I. In papers 6-7, spectrum micro-trading is studied by presenting a model, an ecosystem, performance metrics and simulation studies.

Paper 1 H.N. Pham, P. Grønsund, P.E. Engelstad and O.Grøndalen, "A Dynamic Spectrum Access Scheme for Unlicensed Systems Coexisting with Primary OFDMA Systems", in Proc. 7th IEEE annual Consumer Communications and Networking Conference (IEEE CCNC), Las Vegas, Nevada, Jan. 9-12, 2010.

Paper 2 O. Grøndalen, M. Lähteenoja and P. Grønsund, "Business case proposal for a Cognitive Radio Network based on Wireless Sensor Network", in Proc. 5th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), Cannes, France, Jun. 9-11, 2010.

Paper 3 P. Grønsund and O. Grøndalen, "Performance Of a Sensor Network Aided Cognitive Radio System", in Proc. 22th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE PIMRC), Toronto, Canada, Sep. 11-14, 2011.

Paper 4 J. Park, P. Pawełczak, P. Grønsund and D. Čabrić, "Performance of Opportunistic Spectrum OFDMA Network with Users of Different Priorities and Traffic Characteristics", in Proc. 53rd IEEE Global Communications Conference (IEEE GLOBECOM), Miami, Florida, USA, Dec. 6-10, 2010.

Paper 5 P. Pawełczak, J. Park, P. Grønsund and D. Čabrić, "System Level Analysis of OFDMA-Based Networks in TV White Spaces: IEEE 802.22 Case Study", Book chapter in TV White Space Spectrum Technologies: Regulations, Standards and Applications (by R. A. Saaed and S. J. Shellhammer), CRC Press, Dec. 11, 2011.

Paper 6 P. Grønsund, R. MacKenzie, P.H. Lehne, K. Briggs, O. Grøndalen, P.E. Engelstad, T. Tjelta, "Towards spectrum micro-trading", in Proc. ICT Future Networks and Mobile Summit, Berlin, Germany, July 4-6, 2012.

Paper 7 R. MacKenzie, K. Briggs, P. Grønsund, P.H. Lehne, "Spectrum Micro-Trading for Mobile Operators", Submitted to IEEE Wireless Communications Magazine, 2013.

Acknowledgements

First and foremost, I would like to thank my principal supervisor Paal E. Engelstad for his valuable and constructive cooperation, for supporting me, for being a good colleague and for giving me amazing opportunities. Paal is full of innovative ideas and able to aid me in realizing them. I would also like to thank my informal supervisor, mentor and colleague Ole Grøndalen for all the cooperation, inspiring ideas, support and feedback. Next, I would like to thank my co-supervisor Przemysław Pawełczak for great cooperation, constructive ideas, for inviting me to UCLA and for including me in fruitful cooperations. My thanks also goes to my co-supervisor Audun Fosselie Hansen for helping me into the PhD project, for interesting discussions and feedback.

Next, I would also like to thank my colleagues at Telenor ASA, especially Per Hjalmar Lehne, Terje Tjelta and Markku Lähteenoja for valuable discussion and cooperation, Patrick Waldemar for supporting me and revising the thesis, Nils Flaarønning, Thomas Haslestad and Elin Melby for supporting me and giving me advices. I would also like to thank my colleagues at Simula Research Laboratory and at the University of Oslo, especially Hai Ngoc Pham, Dominic Kaspar and Kristian Evensen in the SimTel lab for cooperation and all the fun, and Pål Halvorsen and Carsten Griwodz for including me at Simula. I would also like to thank my colleagues at the CORES lab at UCLA, especially Danijela Čabrić and Jihoon Park for the inspiring cooperation. My thanks also goes to my colleagues in the EU FP7 projects SENDORA and QoSMOS for valuable cooperation.

I would like to thank my family, my brother and father for constructive feedback, and my mother and sister for supporting me throughput this thesis. Finally, my greatest thanks goes to my wife Tuva for her support, patience, encouragement and love. This dissertation would not have been possible without you. And to my kids, Synneva and Henrik, which give me joy of life every day. This dissertation is dedicated to you.

Oslo, June 2013,

Pål R. Grønsund

Contents

List of Figures

List of Tables

Notations

3G	3rd Generation Mobile System
3GPP	3rd Generation Partnership Project
4G	4th Generation Mobile System
ASA	Authorized Shared Access
BE	Best Effort
BS	Base Station
CAPEX	Capital Expenditures
CBR	Constant Bit Rate
CEPT	European Conference of Postal and Telecommunications Administrations
CPE	Customer Premises Equipment
CR	Cognitive Radio
DSA	Dynamic Spectrum Access
DySPAN	Dynamic Spectrum Access Network
EBITDA	Earnings Before Interests, Taxes, Depreciation and Amortization
ECC	Electronic Communications Committee
EIRP	Effective isotropic radiated power
ERA	Excellence in Research for Australia
ETSI	European Telecommunications Standards Institute
FC	Fusion Centre
FCC	Federal Communications Commission
FP7	Framework Programme 7
FTP	File Transport Protocol
GPS	Global Positioning System
GSM	Global System for Mobile Communications
ICT	Information and Communications Technologies
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
IMT	International Mobile Telecommunications
IRR	Internal Rate of Return
LTE	Long Term Evolution

LSA	Licensed Shared Access
MAC	Medium Access Control
NPV	Net Present Value
NS-2	Network Simulator 2
Ofcom	Office of communications
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditures
OSA	Opportunistic Spectrum Access
OU	Opportunistic User
PAWS	Protocol to Access White Space database
PHY	Physical Layer
PU	Primary User
QoE	Quality of Experience
QoS	Quality of Service
QoSMOS	Quality of Service and MObility driven cognitive radio Systems
REM	Radio Environment Map
RF	Radio Frequency
ROI	Return on Investment
RRS	Reconfigurable Radio Systems
SENDORA	Sensor Network Aided Cognitive Radio System
SDR	Software Defined Radio
SINR	Signal-to-Interference and Noise Ratio
SM	Spectrum Manager
SNR	Signal-to-Noise Ratio
SSE	Spectrum Selector
SU	Secondary User
TDD	Time Divison Duplexing
TCP	Transmission Control Protocol
TVWS	TV White Spaces
UGS	Unsolicited Grant Service
UDP	User Datagram Protocol
UHF	Ultra High Frequency
UWB	Ultra Wide Band
VBR	Variable Bit Rate
VHF	Very High Frequency
VoIP	Voice over IP
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

WLAN	Wireless Local Area Network
WRAN	Wireless Regional Area Network
WM	Wireless Microphone
WSD	White space device
WSN	Wireless Sensor Network

Part I

Chapter 1

Introduction

1.1 Background: Cognitive Radio

The demand for mobile and wireless data is increasing at an explosive rate, driven by the increasing use of laptops, smart phones and tablets. Other emerging wireless services such as machine-to-machine communication for smart metering, smart-grid and medical networks will also contribute to this growth. This increasing usage and demand of wireless systems over the years has caused a dense assignment of licensed frequency bands to operators, which have led to spectrum scarcity. However, despite this incredible demand and spectrum scarcity, several measurements have shown that much of the assigned spectrum is underutilized at given times and locations. A measurement in one of the most densely populated areas in the US, New York, found that only 13% of the spectrum in the range 30-3000 MHz was occupied, in frequency and time [1]. Hence, there exist unused spectrum resources, but most often with the limitation that only the primary user granted rights to use the spectrum license can utilize it. These unutilized spectrum resources are referred to as spectrum holes [2] or white spaces [3]. Peha [4] states that the spectrum shortage comes from outdated regulations, and that new technology will enable much more spectrum sharing.

Cognitive Radio (CR) [3, 5] is an interesting technology that has emerged to solve the spectrum scarcity. The main application of CR is to exploit the spectrum resources more efficiently by opportunistically utilizing white spaces. The CR user is then referred to as the secondary user, which utilizes white spaces in spectrum held by the primary user. From a mobile operator's perspective, CR is an “intelligent” and flexible radio system where terminals and base stations are able to observe and learn from the environment they operate in and adapt accordingly. To observe and learn from the radio environment, CRs typically use spectrum sensing [6] to monitor radio signals from primary users of the spectrum and thereby identify spectrum holes. Another source of information is databases that contain information about current and historical spectrum usage [7]. To adapt, the

CR can use sophisticated and intelligent algorithms to utilize white spaces and increase spectrum efficiency.

1.2 Motivation: Cognitive Radio From a Mobile Operator's Perspective

The main application for CR is to exploit the spectrum resources more efficiently by dynamically or opportunistically utilizing white spaces [8]. At the same time, mobile operators consider their spectrum licenses, which tend to be extensive investments, as one of their most valuable assets. CR therefore has the potential to be a disruptive opportunity for secondary operators, with a disruptive business model, to access valuable spectrum without the need to acquire an expensive spectrum license to provide a wireless service. In this context, CR therefore has the potential to change the way spectrum is regulated and used.

CR is challenging in at least two ways for a mobile operator that has already invested considerably in spectrum resources. First, secondary operators that utilize CRs might exploit available resources in bands owned by the primary operator. This might cause interference in the spectrum bands owned by the primary operator, leading to lower performance and capacity. Second, if the secondary operator uses CR to access white space spectrum and offer similar services as the primary operator, higher competition with the secondary operators might become a challenge [9]. Focusing on these threats of CR, the mobile operator would be reluctant to introduce CR to protect its investments and maintain its market share by preventing competition.

However, there are extensive activities on CR in research [10], standardization [11] and regulation [12, 13] in addition to some commercial activities. Initially, it seems that there will be a hybrid spectrum regime with some spectrum bands being regulated under the traditional static licensing model and some regulated for CR access. Some initial steps in this direction are already evident with the advancement in regulations to allow CRs to opportunistically access spectrum in the TV white spaces (TVWS), i.e. white spaces in the UHF bands allocated for TV broadcasting, by the regulators in the US [14], UK [15] and Europe [16]. Other proposals also emerge such as to allow for opportunistic access by small cells in the 3.5 GHz bands [17]. In the opportunistic spectrum access (OSA) scheme [18], the CR is considered a secondary user that opportunistically utilizes unused spectrum resources held by primary users. Other spectrum management regimes [8] are also envisioned for CR such as the use of market mechanisms to trade unused spectrum [19–21]. Hence, regulators might opt for opportunistic spectrum access by CR, spectrum trading and other dynamic spectrum management regimes when regulating the use of spectrum bands in the future to increase overall spectrum utilization.

Therefore, instead of only focusing on the threats and challenges, the operators should also focus on understanding how they can benefit from using CR in existing or new networks and markets. Since wireless networks are becoming increasingly capacity limited, operators need more spectrum to serve their subscribers' increasing data usage. However, this might be challenging since spectrum is a limited and expensive resource. To get access to more spectrum, operators can use CR to access additional spectrum resources to serve more customers and enhance performance in existing networks that are becoming capacity limited. Mobile operators, which often have the advantage with long experience in operating wireless networks, can also use CR to access spectrum in and to enter new markets where they do not have and cannot acquire a spectrum license themselves.

There are especially three aspects that are of highest importance to the mobile operator when considering deployment of CR systems. First, the operator should understand the technical aspects of CR that allow the operator to enhance spectrum utilization by using white spaces [10, 22, 23]. Performance of CR networks in terms of capacity, throughput, delay and packet loss is vital to the mobile operator to maintain highest possible customer satisfaction. These performance metrics are important to support quality of service (QoS) in CR networks. The operator should be able to reliably detect white spaces with high precision by using a wireless sensor network [24] or spectrum database. A promising solution is the sensor network aided CR (SENDORA) concept [24,25], which will be studied in this thesis. The SENDORA concept aims to reliably detect the primary users by using a wireless sensor network with sensors deployed externally in addition to sensors integrated in the CR terminals. The operator should also be able to characterize the spectrum usage by primary systems [26, 27], to estimate the available capacity for use and to design CR systems able to utilize the available capacity.

Second, a viable business case is crucial for the operator to be willing to invest in and deploy CR systems as compared to using static licensing. Some research exist on business related issues and economic modeling of CR, e.g. [9,28–31]. However, the economic modeling is very dependent on the actual business model, the scenario and use cases used by the mobile operator. Therefore, it is of highest importance to identify and study attractive business cases for mobile operators using CR to access white spaces. These business cases should consider technical constraints and features of CR networks. It is also important to identify the most critical aspects to obtain viable business cases and to evaluate these in detail.

Third, standards for CR systems [32–34] are required for the wireless devices to interoperate [35] and to reach economy of scale. Hence, standards will be considered by mobile operators when deploying CR systems. The first CR standard IEEE 802.22 [36] was initiated in 2004 and finalized, during this thesis work, in July 2011. There exists much research on specific functionalities of IEEE 802.22, e.g. [37–50]. But, to the best of our knowledge, there exist no real life field trials nor any comprehensive system level studies of a complete IEEE 802.22 implementation. Therefore, before deploying a CR system based on such a standard, it is of highest importance to evaluate its performance considering the complete protocol stack. Many aspects should be evaluated such as the standard's potential to support QoS and different applications. Performance should also be evaluated for different sensing strategies, for different primary user activity levels and for other novel features such as cognitive spectrum management functions.

1.3 Research Objectives

The main objective of this thesis is to study and understand how a mobile operator can benefit from using CR to opportunistically access white spaces. The main research question in this thesis is stated as follows:

> **How can a mobile operator benefit from using cognitive radio to opportunistically access white spaces, with the potential to enable sustaining and disruptive innovation?**

This research question is addressed from two perspectives; from a technical system performance perspective and from an economic perspective. From the technical system performance perspective we study the performance considering metrics such as capacity, throughput, delay and packet loss in mobile CR networks. From the economic perspective we study the economic viability of attractive business case scenarios for CR used by a mobile operator. These perspectives are interlinked such that similar scenarios are considered from both perspectives and such that important conclusions in technical studies are used as input to the economic studies, and vice versa.

In our work, it is considered that CR has the potential to enable sustaining and disruptive innovation [51] by focusing on the potential to reduce or remove the costs to access spectrum. Hence, this can potentially lower the costs related to providing wireless services. CR also has the potential to offer higher capacity services if more spectrum is found available. For the wireless services offered by mobile operators to be attractive and to be most preferred by customers, these services mainly compete on different performance metrics. The most important technical performance metrics are throughput and delay, and the most important economic metric is probably the subscription fee. Furthermore, since innovations most often compete on different performance metrics, these technical and economic metrics will be of highest importance for the mobile operator to understand how to benefit from using CR. Also, to understand how it potentially can enable disruptive innovation by introducing a new value proposition, or enable sustaining innovation by increasing performance as valued by the customers [51].

To address the main objective we consider three important areas of CR that, as argued above, are important for a mobile operator to understand how to benefit from using CR. For each of these topics, we identify a set of research questions that we attempt to answer:

1. Spectrum occupancy and potential capacity for CR access in primary OFDMA networks:
   - How can we characterize spectrum occupancy and calculate available spectrum for CR access in the temporal, frequency and spatial dimension in primary OFDMA networks?
   - How can the CR system utilize the potentially available spectrum?
2. Technical performance and economic viability for a mobile operator using the SENDORA concept:
   - What business cases for a mobile operator has highest potential using the SENDORA concept?
   - What are the most critical aspects for achieving viable business cases?
   - Are there any critical aspects that will limit the introduction of these business cases?
   - What is the performance and capacity of mobile networks based on the SENDORA concept in terms of throughput, packet loss and delay?
3. Performance of the first CR standard IEEE 802.22:
   - What is the performance in terms of throughput, packet loss and delay?
   - Can QoS be supported?
   - How does different primary user activity impact performance?
   - How do different sensing strategies impact performance?
   - How can statistical models based on historical sensor measurements be used to increase performance?

To address the research questions for each of the three areas for CR given above, we use the following approaches:

1. To characterize spectrum usage in primary OFDMA systems, we use a system level simulation model for the IEEE 802.16 standard [52] based on OFDMA. Based on this characterization we calculate the available capacity for use by CR systems and discuss how a CR system can be designed to use the available capacity.
2. To address the economic perspective we propose and evaluate business cases that are attractive for a mobile operator using the SENDORA concept. Second, to address the technical performance perspective we implement a complete SENDORA system in a detailed system level simulator.
3. To evaluate performance of the IEEE 802.22 standard we implement the complete protocol stack of a CR system based on this standard with novel features in a detailed system level simulator.

1.4 Scope of Thesis

The research field of CR is wide as will be described in Chapter 2. Therefore, we limit the scope of the research on CR in this thesis as described in the following. The overall scope of this thesis is characterized by the objective and focus on CR from a mobile operator's perspective.

The spectrum management technique considered is opportunistic spectrum access (OSA), where the CRs as secondary users opportunistically access "unused" spectrum that is held by primary users. The CR users must be aware of the spectrum used by primary users. This is achieved by using spectrum sensing and getting information from a spectrum database.

Since mobile operators generally use centralized networks, we focus on centralized CR networks with base stations or cognitive femtocells responsible for controlling the CR terminals. In a centralized CR network, the base station or cognitive femtocell and CR terminals cooperate by reporting spectrum sensor measurements to a centralized controlling unit. This centralized unit is usually the base station, which is responsible for allocating spectrum to the CR users. In addition to the base station, we also consider other complementary centralized units such as a fusion center and a spectrum database. A centralized fusion center is used in papers B-E to collect sensor measurements and determine which channels that can be used by the CR system. A centralized spectrum database is considered in papers F-I that provide information to the CR system about available spectrum.

Mobile operators prefer standardized systems when deploying mobile networks. Therefore, we consider different standards that may evolve for CR when evaluating technical performance and economic viability, i.e. IEEE 802.22, IEEE 802.16 and Long Term Evolution (LTE) [53]. These standards use centralized networks with a base station controlling the CR users.

The main focus is on the system level performance of CR systems in the technical evaluations. We focus more on the medium access control (MAC) layer rather than the physical layer. Therefore, the energy detector is used for spectrum sensing, which is simpler to implement at the physical layer in our simulation models. Novel sensing schemes are implemented at the MAC layer.

For spectrum allocation, we focus on cooperative spectrum sharing where the CR users share information about primary user appearance and interference measurements. This is usual in centralized CR networks as opposed to non-cooperative where the CR users only consider their own measurements.

For spectrum sharing, we focus on intra-network sharing for one CR network with the main issue of not causing interference to the primary network. To limit the scope we do not consider inter-network sharing where multiple CR networks are operating in the same region. Inter-network sharing is important and is therefore considered for further work.

1.5 Methodology

1.5.1 Overall Research Design and Methodology

The overall research design and methodology used is illustrated in Fig. 1.1. The first main research focus is on performance evaluation of the technical feasibility of CR networks. This is done by modeling and simulating CR networks. The second main focus is to evaluate the economic viability of using CR networks. This is done by evaluating business cases that are attractive to mobile operators and to identify the most critical parameters to achieve viable business cases. The research methods used for simulations and business case analysis will be described below.

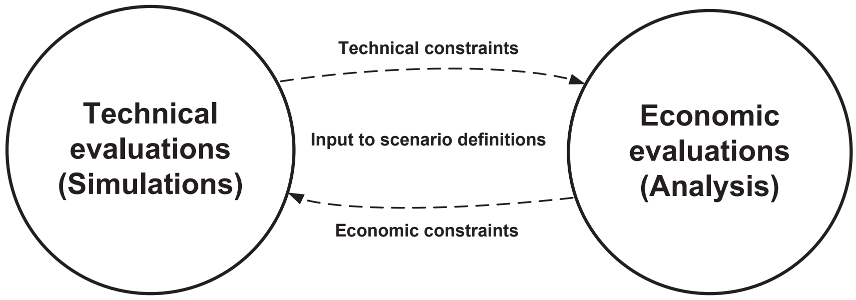


Figure 1.1: Overview of overall research design used in this thesis.

The arrows between the research activities illustrate that results in one research activity is used as input to the other research activity. Similar scenarios are evaluated in some of the simulation models and business case models. These scenarios have a strong focus on a mobile operator's perspective. First, some of the critical aspects identified in the business case analysis are subject for further performance and capacity evaluation by using the simulation models. Second, conclusions drawn from the simulation studies are used as input to and serve as new hypotheses for further business case evaluations. As an example of the first, the business case study in Paper B concludes that reuse of existing base station sites is critical for a viable business case. Performance and capacity when reusing existing base station sites are then evaluated further in the simulation models in papers C and D. As another example of the second, through simulation studies it is identified in Paper C that smaller cells such as femtocells are more suitable for the deployment of CR networks. A business case based on cognitive femtocells used to offload the macro network is then evaluated in Paper E.

Scenario analysis is a central part in both the technical and economic evaluations. This consists in identifying, selecting and refining scenarios that are considered attractive for mobile operators. CR scenarios can be classified according to the dynamic spectrum access (DSA) method [8] and according to economic scenarios such as presented by Barrie et. al. [54] and Weiss and Lehr [55]. These classifications are important for several parameters in the technical economic evaluations. Furthermore, there are many important aspects concerning technical, economic and regulatory constraints and feasibilities for the scenarios [56–58] to be considered when defining the scenario. The most important ones are the spectrum context awareness approach (sensing, database, CPC), market mode (OSA, trading, LSA), QoS provided (best effort, guaranteed bit rate, delay, loss tolerance, bandwidth), application (data, voice, video), mobility level (mobile, nomadic, static), environment (urban, suburban, rural, indoor), communication range, regulatory remarks (allowed transmit power level, spectrum band), and terminal type (smart phone, laptop, customer premises equipment). For specific scenarios, it can also be important to consider features and limitations of specific wireless standard used (LTE, IEEE 802.22, IEEE 802.16). The focus of this thesis is on wireless and mobile broadband scenarios for CR only, but with different parameters as discussed above.

The research presented in this thesis is highly relevant since CR, after more than a decade of research, is currently evolving from the research domain into the commercial domain. Another important factor for the relevance of this research is that mobile operators have challenges with identifying the potential performance gains and business opportunities that CR can bring.

1.5.2 Method for Technical Evaluations

Computer science can be defined as *the study of the principles and use of computers*. Furthermore, computer science has many subfields with various theoretical and practical nature. Networking is one that concerns the study of algorithms and protocols for communicating data across different media, encompassing both wired and wireless networks. Three scientific methods are used in computer science [59]. First, theoretical computer science adhere to the tradition of logics and mathematics and follows the classical methodology of building theories as logical systems with stringent definitions of objects (axioms) and operations (rules) for deriving and proving theorems. Second, the experimental computer science approach is used both for theory testing and for exploration. Third, simulations makes it possible to investigate and study phenomena that cannot be replicated in laboratories, such as emerging technologies that do not exist for experimental research. Theory, experiment and simulation are all about models of phenomena. One common thing to all of these methods is the use of modeling, since the phenomena to be studied most often must be simplified. A simplified model of a phenomena means that we have a sort of description in some symbolic language, which enables us to predict observable and measurable consequences of given changes in a system. A model must take into account the relevant features of a phenomena, which often are based on theory.

Three main methods for evaluating performance of computer systems are described in [60]; measurements, analytical modeling and simulation. These can be used to evaluate performance of CR networks. Measurements can be based on experimental research or empirical research [61]. Experimental research would typically consist in setting up a CR network, conduct experiments and collect measurements. Empirical research would typically consist in extracting measurements from already deployed CR networks that are in use. Both these approaches are challenging for the research presented in this thesis since the technologies used are immature and expensive if existing at all. Analytical modeling is often used to analyze different functions and algorithms for CR networks. There is a challenge when modeling complete CR networks in that these are often too complex to be modeled with analytical models. However, analytical modeling is suitable for the modeling of certain functionality and algorithms of CR networks. Analytical modeling is used in Paper F.

The simulation method is widely used in the scientific research field to model and evaluate the performance of physical systems such as communication systems [59]. A computer simulation is an attempt to model a real-life or hypothetical situation on a computer. By changing variables in the system, predictions can be made about the behavior of the system. The specific process used for the computer simulations can be described by four major steps [62]; model and implement the system in the simulator, set up the simulation scenario, run simulations, and analyze the simulation results.

It should be emphasized that the simulation method as a scientific method is iterative. Continuous calibration, verification and validation of the simulation model is important to produce accurate simulation models. Model calibration is done by adjusting any available parameters in order to adjust how the model operates and simulates the system. Model verification is achieved by obtaining output data from the model and comparing it to expectations based on the input data. Model validation is done by comparing the results with expectations based on historical data and theories in the research community.

We mainly use the discrete event simulation model to model the CR networks as event-based dynamic (stochastic) systems. In such models, each event in the simulator occurs at an instant in time and marks a change of state in the system [62, 63]. Specifically, we use the network simulator NS-2 [64] (Papers A, C, D and F-I), which support state-of-the-art protocols for wireless and wired networks. All layers of the TCP/IP communication protocol stack are implemented in the NS-2 simulator. The focus of the studies in this thesis is on implementing the MAC and physical layers specific for CR systems. We also implement centralized servers for spectrum management. The simulators NS-3 and Omnet++ were also evaluated at the beginning of implementing the simulation models in 2009, but it was found that NS-2 had the best implementation of OFDMA and the IEEE 802.16 standard [65]. Also, NS-2 is widely used in the research community. We use the implementation of the IEEE 802.16 standard in NS-2 as basis when implementing the simulation models in papers A, C, D and F-I. Common for all the simulation models implemented is that a cellular network is considered where centralized base stations provide wireless access to mobile devices using CR technologies.

Fig 1.2 illustrates the workflow of the simulations used in this theses. The simulations are run in the network simulator NS-2 implemented in the programming language C++[1]. The scenario definition is implemented using Python[2] and Otcl[3] and consists in defining the network topology, the traffic and application sources, the mobility pattern and setting the system parameters and functionalities. The NS-2 simulator provides output to logfiles. A python program is then implemented to extract the most relevant results from the logfiles and Matlab[4] is used to analyze and display the results. The loop in the workflow illustrates the importance of using the results as feedback to the refinement of the simulator implementation and to the scenario definition.

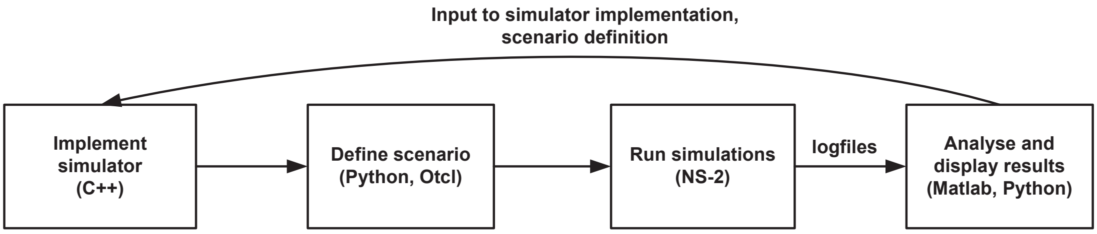


Figure 1.2: Workflow and tools used in NS-2 computer simulations.

There are also challenges with the simulation method that should be considered. A first challenge is that as the complexity and number of elements in the simulation model increases, the simulation time increases [60]. This might limit the scope of the simulations and scenarios that can be evaluated. As an example, if the simulation model is complex with many events, the simulation scenario could be constrained to a limited number of users. It might also limit the number of simulations that can be run to obtain results of high accuracy. A second challenge is that several assumptions must be made to model the real system behavior, and some of these assumptions might be uncertain. Examples of such assumptions for a CR system include the propagation model, the traffic model of different users and applications, and the node mobility model. Third, when there are many parameters to be set and protocol features to be implemented in complex systems such CR systems, there is always a risk that an error is overlooked. The iterative loop in the simulation method aims to reduce this risk.

1.5.3 Method for Economic Evaluations

Business case studies are used to identify business viability and to identify business critical aspects for the use of CR networks. Financial modeling [66] is used to build these business

[1]C++ is a general-purpose object oriented programming language that comprises a combination of high- and low-level language features.

[2]Python (http://www.python.org/) is a general-purpose, high-level programming language.

[3]OTcl (http://otcl-tclcl.sourceforge.net/otcl/) is an extension to the scripting language Tcl/Tk for object-oriented programming.

[4]Matlab (http://www.mathworks.com/) is a high-level language and interactive environment for numerical computation, visualization, and programming

cases. Financial modeling can be described as the task of building a model of a financial decision making situation. This is a mathematical model designed to represent the performance of a financial asset or portfolio of a business, a project or any other investment. There are different applications of financial modeling such as in corporate finance and in quantitative finance. We focus on corporate finance when analysing the business case for a mobile operator using CR.

In the business case analysis, we use traditional (discounted) cash flow analysis to get an indication of the profitability. The cash flow is usually the income (revenues) subtracted by cost (investments and operational costs) for a given time period, but cash flow can also be calculated for costs only. A business case is often organized around a single action or single decision and its alternatives. The focus is on that specific action (e.g. CR service). The business case predicts cash flow figures and based on that, other financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), and payback period. The business case is based on models for revenues and costs that are customized for the case and applied to one or more action scenarios.

The business case model is built to use a set of input parameters (e.g. revenues, costs) that are subject to detailed evaluation. Furthermore, the impact of each input parameter on the financial metrics defined can be evaluated through sensitivity analysis, that is changing one parameter (e.g. a particular revenue) and see how this affect the economic metrics (e.g. NPV). The input parameters that are most sensitive in the business case are those that affect the economic metrics most. These will often be considered as critical parameters subject for further research. Critical input parameters that affect the technical parameters impacting performance in CR networks can then be evaluated further in the computer simulation models.

The workflow of the business case study is illustrated in Fig. 1.3. Excel is the main tool used for the business case analysis, cash flow analysis and sensitivity analysis. The loop in the figure illustrates that results from the cash flow and sensitivity analysis are used to refine the model by optimizing the business case scenario and assumptions.

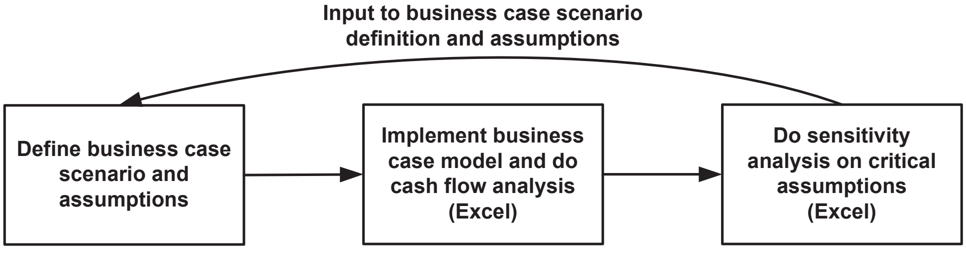


Figure 1.3: Workflow of business case study.

It must be emphasized that the business cases and the studied concepts are innovative and that the business cases are evaluated for a period that is many years into the future when the technology is expected to be in the market. Hence, the assumptions concerning parameters and technology functionalities are uncertain. Therefore, as the most important message of the business case analysis, sensitivity analyses are used to reveal the most critical aspects of the business cases.

1.6 Scientific Contributions

The scientific contributions of this thesis are represented by nine papers in peer-reviewed conferences and journals (papers A-I). Fig. 1.4 gives an illustration of the contribution by each paper grouped by the subject area, as well as showing the progression and quality of the research. The main scientific contributions are:

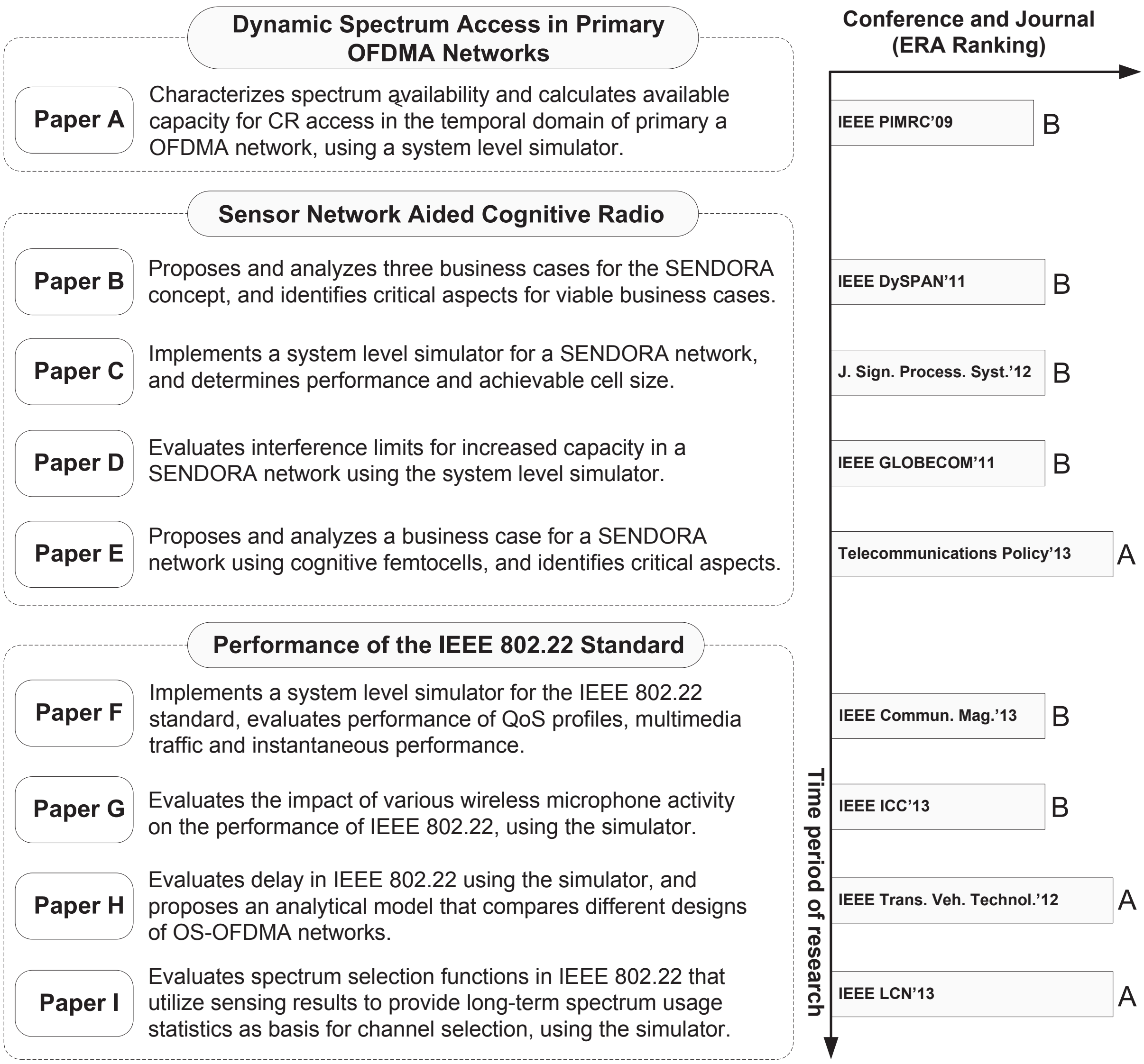


Figure 1.4: Overview of scientific contributions in this dissertation. Conferences and journals with ranking according to ERA [67] are given to the right.

Paper A We characterize the spectrum occupancy and calculate the potential capacity for CR access in primary OFDMA networks, using a system level simulator of the IEEE 802.16 standard with various traffic models. It is shown that there is a potential for CR to access white spaces in primary OFDMA networks in the time domain. We conclude that cooperation and assistance from the primary operator is important to maximize spectrum utilization.

Paper B We propose and evaluate three business case scenarios for deployment of SENDORA systems; "spectrum sharing", "spectrum broker" and "new entrant". The business case analysis show that the "spectrum sharing" business case, where a joint venture gets the rights to use the "unused" spectrum resources of spectrum owners in a cognitive way, is one of the best possible cases for an operator deploying a mobile network based on the SENDORA concept. It is also shown that it is challenging to make a viable business for a new entrant using the SENDORA concept. We show that the most critical aspects are the fixed sensor density, the fixed sensor operational costs and the number of new cognitive base station sites required.

Paper C We implement a detailed system level simulator for a SENDORA network using the IEEE 802.16 standard. This simulation model is used to determine the performance and achievable cell size in a SENDORA system when deployed with CR base stations co-located with primary base stations that uses a cellular reuse pattern with seven frequencies. It is shown that the capacity not is acceptable with full co-location, but that good capacity can be achieved for smaller cell sizes. This points in the direction of shorter range, smaller and less expensive BSs for the secondary system such as WiFi access points and femtocells.

Paper D We study how relaxed requirements for the maximum interference generated by the secondary CR transmitters to the primary system can improve secondary system performance and capacity in a SENDORA system. The simulation model in Paper C is extended to use different interference limits for the CR. It is shown that interference limits for the CR can be found that allow full throughput and coverage for the secondary system. It is found that this comes at the cost of a slight reduction in throughput and increase in packet loss for the primary system.

Paper E We propose and evaluate a business case where a mobile operator offloads its LTE network by deploying cognitive femtocells based on sensor network aided CR technology. The business case analysis illustrates that there is a potential for cost savings when offloading the mobile network with cognitive femtocells compared to an alternative strategy with conventional femtocells and additional base stations. It is shown that the price for backhauling the cognitive femtocell and the number of users supported by the cognitive femtocell are the most critical parameters to obtain a viable business case, but that sensor network costs are less critical when sensors are embedded in the cognitive femtocells.

Paper F We implement a detailed system level simulation model for a CR network based on the IEEE 802.22 standard that uses novel spectrum sensing strategies and wireless microphones as primary users in the TV white spaces. QoS profiles are evaluated and it is shown that the guaranteed bit rate QoS service for VoIP is prioritized, though the spectrum sensing strategy used is important to satisfy strict QoS requirements. It is also shown that delay increases with respect to the overhead caused by the sensing strategy used, and that VoIP traffic can be prioritized to achieve lowest possible delay for the specific sensing strategy irrespective of the best effort traffic load.

Paper G We use the same simulation model as in Paper F to evaluate the performance of the IEEE 802.22 standard with sensing functionality, when considering the effect of different spatiotemporal activity levels for wireless microphones. It is shown that the activity of wireless microphones should be quite high in order to reduce throughput and increase delay. Furthermore, it is shown that interference to the wireless microphones is low in general and occurs only for short intervals when the wireless microphone appears.

Paper H We first propose an analytical framework to quantitatively assess the performance of a network based on opportunistic spectrum access using OFDMA, considering features such as channelization structure, subcarrier allocation, resource assignment, different spectrum sensing methods and QoS classes. The performance evaluation suggests that opportunistic spectrum access using OFDMA with subchannel notching and channel bonding could provide almost ten times higher throughput compared with a design without those options, when the activity and density of wireless microphones are high. We also evaluate the impact of various wireless microphone activity levels on delay performance in IEEE 802.22 using the system level simulation model as used in papers F and G. It is shown that delay increases as the wireless microphone activity increases due to an increase in the number of channel switches and since the probability of obtaining an available channel reduces.

Paper I We propose and evaluate three spectrum selection functions that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection to enhance performance by reducing interference and increasing throughput. These are implemented in the system level simulation model for IEEE 802.22 used in papers F-H. It is shown that the spectrum selection functions reduce the harmful interference for both the IEEE 802.22 network and the wireless microphone, which results in a more stable network with higher system throughput.

1.7 Thesis Outline

The thesis is organized as follows:

Part I Consists of chapters 1-4 and provides an overview of our work.

- **Chapter 1** *Introduction*
- **Chapter 2** *Background*: provides an overview of CR and presents background relevant to different dimensions of CR that is related to the work in the papers A-I included in this thesis.
- **Chapter 3** *Contributions of Papers*: gives a summary of each of the papers A-I, also including related work specific for the paper and the contributions of the paper.
- **Chapter 4** *Conclusions*: gives a conclusion of the work, a summary of the research and scientific contributions, as well as discussing limitations of the research and proposing directions for future work.

Part II Contains the papers A-I included in this thesis.

Chapter 2

Background

This chapter gives an overview of CR and presents background relevant to different dimensions of CR that is related to the work in this thesis. More details on related work for each paper will be given with the summary of the papers A-I in Chapter 3. This background chapter contains six sections. The first section gives a definition of CR before the second provides background on technical aspects of CR. The third gives an overview of the SENDORA concept relevant for papers B-E. In the fourth section an overview is given on the current activities in standardization and regulation for CR, which especially is relevant for papers F-I. The fifth section gives an overview and discussion on business aspects of CR. Finally, an overview is given on relevant scenarios for CR. The relation to the work and papers in this thesis will be clarified as the background is presented.

2.1 What is Cognitive Radio?

Cognitive radio has been a research subject since the concept was coined by J. Mitola [5,68] in the late 1990s, with the definition [5]:

> *Cognitive radio identifies the point at which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to, detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.*

J. Mitola and G.Q. Maguire stated in [68] that CR extends the software radio with radio-domain model-based reasoning about radio etiquettes, that is the set of radio frequency (RF) bands[1], air interfaces, protocols, and spatial and temporal patterns that moderate the use of the radio spectrum. A software-defined radio (SDR) is a radio that can accommodate a significant range of RF bands and air interface modes through software [5]. Hence, software-defined radio can be considered an enabler for CR.

[1]Radio frequency (RF) band and spectrum band will be used interchangeably throughout this thesis.

Haykin [3], gave the following definition of CR with more focus on spectrum utilization:

> *Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind; highly reliable communications whenever and wherever needed, and efficient utilization of the radio spectrum.*

One of the main applications of CR is dynamic spectrum access (DSA) [8], which aims to increase utilization of spectrum by using spectrum management models and methods to access spectrum more dynamically. It should be noted here that CR represents a much broader scope for different applications, than DSA only, that can be used to improve wireless communication systems. DSA also has broad connotations that encompass various approaches to spectrum reform [8]. There exist many classifications and taxonomies of CR in the literature [8, 54, 55, 69, 70]. These are based on different classification criteria such as access mode, market mode or scenario. A much used classification of spectrum management for DSA is given in Fig. 2.1.

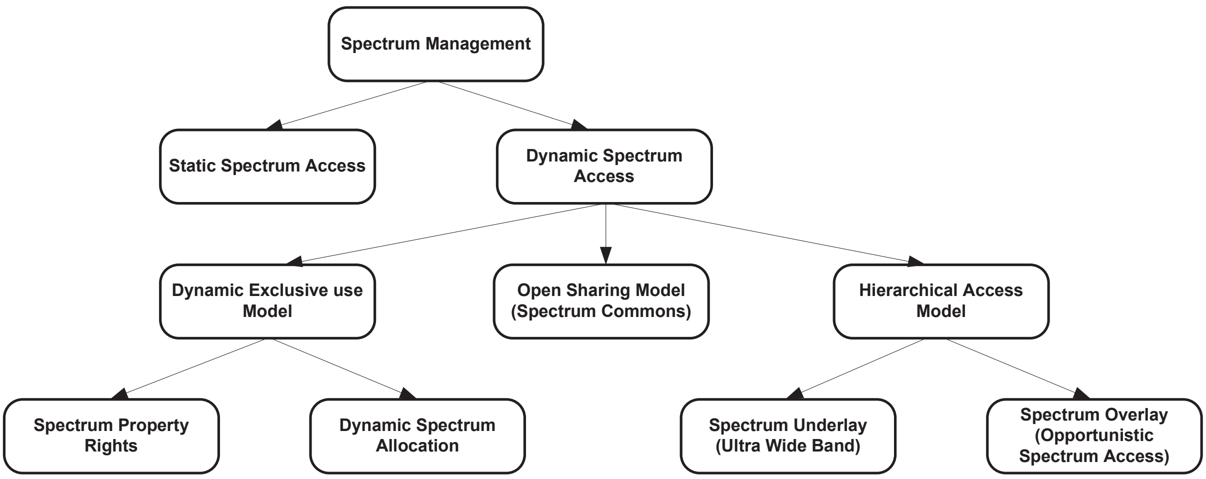


Figure 2.1: Classification of spectrum management (see also [8, 18]).

On the top level, the spectrum management method can either be static or dynamic. For DSA, there are three different classes as described in the following. First, DSA is classified into dynamic exclusive use where spectrum users are given exclusive license like in the static model. But it differs in that it is more flexible such that channels are allocated dynamically among the licenses. Dynamic exclusive use can further be divided into the spectrum property rights [71] and dynamic spectrum allocation [72]. In the spectrum property rights approach, the licensees can sell, lease or trade the rights to use spectrum and there are no restrictions on which technology to use. The market will thus decide by whom and which technology the spectrum will be used, which will lead to the most economic profitable use of the spectrum. In the dynamic spectrum allocation approach the spectrum can be assigned more dynamically in time and geography to improve spectrum utilization. This model enables a more dynamic spectrum market and is usually governed by the spectrum regulator. It will be similar to the current policy where spectrum is allocated to operators for exclusive use, but the spectrum allocation varies on a much faster scale in time and geography.

Second, in the open sharing model users compete for spectrum on equal terms. This model is more commonly referred to as the spectrum commons model with the main practical example being the ISM band used for WiFi. In this approach, limits might be put on the maximum allowed transmit power.

Third, in the hierarchical access model, primary users (PUs) that own a license for spectrum have highest priority to use the spectrum over secondary users (SUs)[2] that can access the spectrum if available. Furthermore, the hierarchical access model can be realized with two approaches. First, in the spectrum underlay approach the SU operates below the noise floor of the PU by spreading the transmitted radio signal over a wide band with low transmission power. This is often referred to as ultra wide band (UWB) [73] achieving high bitrates at short ranges. Second, in the overlay approach also referred to as opportunistic spectrum access (OSA) [18], the SU exploits the spectrum holes in the primary license band in one or more of the spatial, temporal and frequency dimensions. The main focus of this thesis is on the overlay OSA approach. It was noted above that spectrum trading is foreseen in the spectrum property rights approach, but it should also be noted that approaches to use trading of maximum interference limits from the SU to the PU can be possible under the hierarchical access model.

2.2 Spectrum Management for Cognitive Radio

The main requirement for CR under the OSA approach is that it should enable CRs to access primary licensed spectrum while protecting the PUs from interference. Note that a maximum level of interference could be agreed between CR and PU. To achieve this, some basic spectrum management tasks for the CR can be defined and illustrated with the cognition cycle [3, 5, 74–76] in Fig. 2.2, and described as follows [22]:

Spectrum sensing is used to monitor the operating and potential spectrum bands in order to detect spectrum holes and radio signal strength (RF stimuli).

Spectrum decision is used to select spectrum based on information from the spectrum sensing module according to information about QoS requirements and spectrum poli-

[2] CR and SU will be used interchangeably throughout this thesis.

cies. Prior to selection, the spectrum is characterized in terms of radio environment and statistical behavior of the PU.

Spectrum sharing is used to coordinate spectrum access between multiple CR users to prevent interference and collision.

Spectrum mobility is used to switch to a vacant channel when a PU is detected in the operating spectrum.

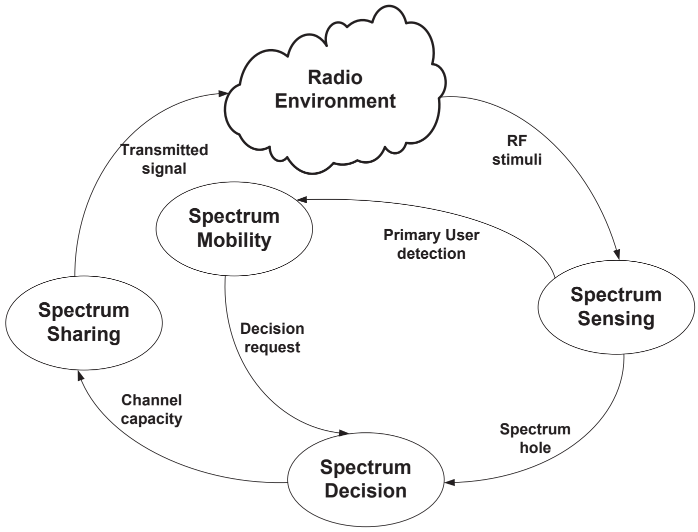


Figure 2.2: Cognition cycle for the spectrum management tasks in Cognitive Radio (recapitulated from [22, Fig. 3(b)]).

It is also noted by Akyildiz et. al. [22] that the spectrum management functions require a cross layer design approach since each function is related to several layers in the TCP/IP stack. The main focus in our papers is on the system level performance of CR networks. Hence, all steps in the cognition cycle are involved in the studies. However, each task is not studied to the same level of detail. The reminder of this section will give a more detailed background on each of the steps in the cognition cycle.

2.2.1 Spectrum Sensing and Spectrum Hole Detection

The CR uses sensing to detect spectrum holes and to protect PUs. Alternative methods exist for obtaining spectrum information, such as spectrum databases [7] and cognitive pilot channels (CPC) [77]. These alternative methods are not visible in the cognition cycle in Fig 2.2, but can complement or replace the sensing functionality.

There are three main sensing techniques that have been used in traditional CR systems [6, 78]; energy detection, matched filter detection and cyclostationary feature detection. The sensing technique used in our papers is the energy detector [36, Section C.1.1], which is simple in that it determines if a signal is present or not on a channel by comparing the energy of a sensed signal with a given threshold. The main challenge with the energy detector is that it is susceptible to error if the noise power is not known [79]. The other sensing techniques are more advanced. Matched filter searches for a known pattern such as reference signal, pilot bits and pilot carriers on the processed signal. Hence, a-priori knowledge about the PU signal and perfect frequency synchronization with the PU is needed. Cyclostationary feature detection does not require perfect frequency synchronisation and sampling since the signals are characterized as cyclostationary where their statistics, mean and autocorrelation, exhibit periodicity. As explained in the thesis scope in Section 1.4, we mostly focus on system level performance of CR networks in papers C-D and F-I. Therefore, we consider energy detection at the physical layer, which is simpler to implement in our simulation models. However, we consider realistic sensor implementations and assumptions for probability of detection and false alarm.

Individual sensing is often not adequate for reliable detection of PUs due to shadowing and multipath propagation. This can be addressed by using cooperative sensing and decision making to reduce the probability of interference to PUs [6, 80]. It is shown that collaborative sensing significantly increases the probability of detection as the number of collaborative sensing nodes increase [81]. However, the increase in probability of detection due to the increase in the number of collaborative sensors comes at the cost of an increase in false alarms [45, 82, 83]. These effects are especially shown in papers F-I, where cooperative sensing is used. It is concluded by Ghasemi et. al. [82] that maintaining the global probabilities of detection and false-alarm at a desired level, collaborative detection enables users to employ less sensitive detectors by lowering the required time-bandwidth product for the individual energy detectors. Papers C-D and F-I in this thesis uses collaborative sensing with the OR rule such that the channel is considered occupied if one of the sensors detect a PU above the detection threshold. One reason for using the OR rule, is that this is mandatory in the US as specified by the IEEE 802.22 standard [36, Sec. 8.6.1.3].

In our papers we mostly focus on sensing schemes at the MAC layer. Sensing algorithms at the physical layer detect the presence of PU signals and deal with metrics for probability of detection and false alarm as functions of the receiver signal-to-noise ratio (SNR) and detection threshold. An energy sensor implementation at the physical layer is given in Paper I. Sensing schemes at the MAC layer deal with issues such as how often to sense and which order to sense channels [44]. Sensing schemes at the MAC layer can also be adaptive by e.g. deciding which channels to sense based on channel statistics [84]. In papers F-I, three sensing schemes are implemented at the MAC layer, all using energy detection at the physical layer. Their impact on the system level performance is evaluated by focusing on the higher level metrics such as throughput, delay and packet loss. The first and most basic is the simple "single-stage" sensing which senses for a given time period with given intervals in between. The second is the "two-stage" sensing used in the IEEE 802.22 standard [36]. At the coarse sensing stage (first stage) a simple sensing technique such as the energy detection is used for frequent and short sensing periods. If coarse sensing detects a PU signal it switches to the fine sensing stage that uses a more detailed sensing technique with a longer sensing period. In papers F-I, coarse sensing detection immediately triggers fine sensing as considered in [85]. Alternatively, the coarse sensing results can be used to decide whether the next scheduled fine sensing period should be executed or cancelled as considered in [48–50]. If a PU signal is detected by fine sensing then the operating channel is switched to one of the backup channels. Quiet periods for the sensing periods are scheduled such that all CR nodes stop transmitting to not interfere with the sensing periods. In papers F and I, we also consider the two-stage consecutive sensing scheme proposed by Jeon et. al. [85]. This sensing scheme is similar to two-stage sensing, but a given number of coarse sensing detections higher than one is needed before the fine sensing period is triggered. The aim is to reduce the impact of false alarms and, hence, reduce total sensing time.

2.2.2 Spectrum Decision

Spectrum decision usually consists of two steps [22]; spectrum characterization and spectrum selection.

Spectrum Characterization

To decide on which spectrum to use, each spectrum band is characterized. This can be based on at least four context awareness approaches [26]; local sensing information by CR users, sensor networks, cooperative networks, or spectrum databases that also could build statistical information about primary networks. Each of these context awareness approaches can be used as stand-alone, or they can be used together to complement each other. The characterization of spectrum considers parameters defining the spectrum band such as the operating frequency, bandwidth, interference to and from PU, path loss, link errors and link delay.

In essence, all spectrum resources that are underutilized in one or more of the spatial or temporal dimensions could be suitable for CR under the OSA approach. However, the spatio-temporal operating context of spectrum in specific environments matters to the selection of the appropriate technology for learning context information. Twelve potential operating contexts for spatio-temporal environments are identified by Weiss et. al. [26]. First, they characterize the spatial dimension as static (spectrum usage not changing), periodic (spectrum usage change at repeating specific periods) or stochastic (spectrum usage change at random periods). Second, the temporal dimension is characterized as static, periodic, fast periodic or stochastic. For instance, TVWS, as considered in papers E-I, is characterized as static in both the temporal and spatial dimensions [26]. However, it should be noted that this is for TV broadcasters and not for wireless microphones as considered in papers F-I. For wireless microphones the spectrum characterization will be more periodic or stochastic in both the temporal and spatial dimensions. A cell site using the LTE standard [86], which is similar to the IEEE 802.16 standard [52] as considered in papers A and C-D, is characterized as temporal fast periodic and spatial stochastic [26]. In Paper A, it is furthermore found that the fast periodic time period in IEEE 802.16 has a temporal stochastic characteristic when the PU traffic load varies. Other characteristics are given for WiFi as temporal stochastic and spatial static, and rotating antenna radar as periodic in both temporal and spatial dimensions [26].

As an example, Fig. 2.3 gives a measurement of already assigned spectrum that is underutilized in the spectrum range 400-1000 MHz. The measurements were taken before the digital dividend spectrum bands, 790-862 MHz, have been assigned to mobile broadband services. Also, a resolution bandwidth of 3 MHz was used for the measurement. However, it is seen that there are still white spaces that potentially can be used by CR. This is especially observed in the TV bands in the range 470-862 MHz as considered in papers E-I. Again, it should be mentioned that the PUs considered in papers F-I are the wireless microphones, which both can transmit at random and periodic times and locations. Similar measurements are presented in [26] over a longer period, where it is also shown that TV bands are free for some hours during night when TV transmitters are shut off.

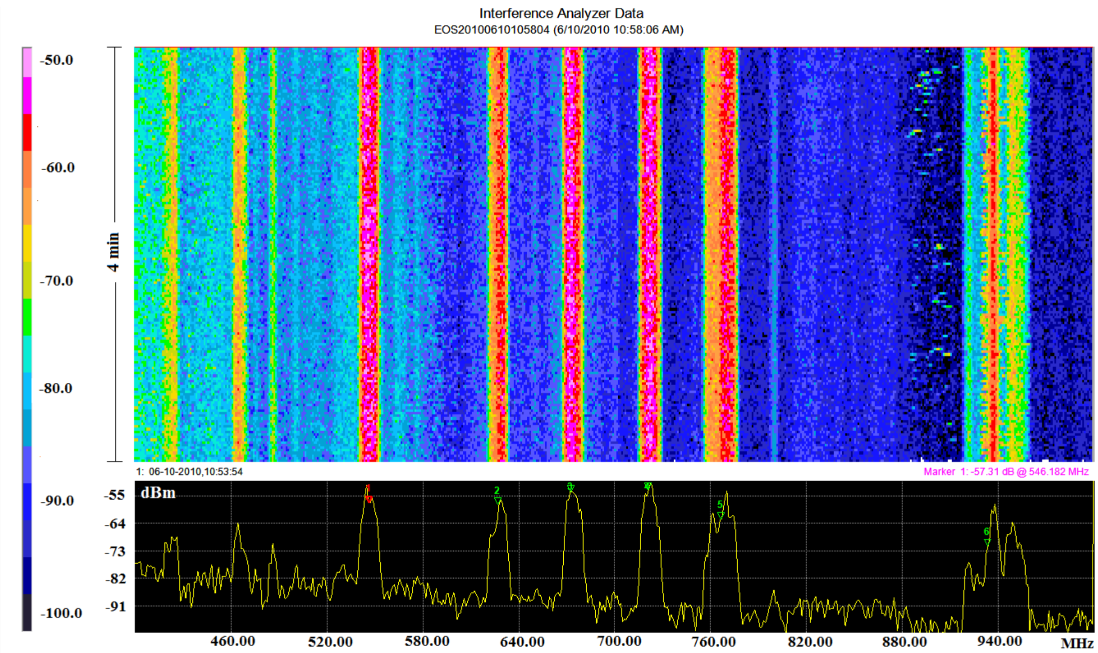


Figure 2.3: Spectrum measurement in the spectrum range 400 to 1000 MHz at Telenor headquarter at Fornebu, Norway, 6 October 2010 (measurement bandwidth resolution is 3 MHz in office environment with potential interfering sources).

Interestingly, from the spectrum occupancy measured over a time period of 4 minutes in the morning given in the top palette in Fig. 2.3, it is seen that the spectrum band for GSM downlink traffic (935-960 MHz) is quite occupied, but that there are many unused spectrum time slots in the spectrum band for GSM uplink traffic (880-915 MHz). This indicates that there could be a potential for CR and DSA in this spectrum band. An occupancy of about only 4% in this band is also identified in [27], but it is notified that it might be more challenging to detect uplink signals due to the lower transmit powers by the GSM terminals as compared to downlink signals by the base station. Hence, it might be challenging to use CR in this band. Approaches with operator assistance as advocated for in Paper A could be investigated further for this spectrum band.

Statistical information about spectrum usage in the temporal dimension could be historical appearance and departure time of PUs. As an example of this, Arshad and Moessner [87] develop a model that characterizes the number of spectrum opportunities available using the probability and approximation theory with an ON-OFF model. A similar model is implemented in Paper I, where instantaneous spectrum characterization is combined with statistical information from historical sensing measurements. Sensing measurements are used to determine the average busy and idle channel times, i.e. the average ON and OFF times. The reason for characterizing spectrum use with this statistical model in Paper I, is that wireless microphones as the PU often appear at specific venues and times such as in the mornings at schools, in the evenings in concert halls or on Sundays in churches.

In papers C-D, spectrum is characterized with focus on the spatial dimension for a set of frequency bands based on measurements from a fixed deployed sensor network. These sensor measurements are reported to a fusion center that creates a map of the received signal powers from the sensors, which is used to allocate channel and allowed transmit power to the CR system. This map of received signal powers can also be referred to as a radio environment map (REM) with imperfect knowledge, e.g. [88]. Such a REM can further be used to improve performance of CR networks by applying case and knowledge based learning algorithms on the REM [89]. Spatial statistics techniques are introduced by Wellens et. al. [90] as methods to describe spectrum usage. They discuss two approaches to spatial modeling of spectrum, a deterministic approach based on a system model of the complete radio environment and an empirical approach that exploits passive measurements of the spectrum use. They show that differences in empirical models can be well explained using results of the deterministic evaluation.

Spectrum Selection

When the spectrum is characterized, the CR user selects the most appropriate spectrum band based on this characterization that best satisfies its QoS requirements such as throughput, delay and packet loss. As an example, in [87] and Paper I, as discussed above, the spectrum selection consist in selecting the channel with highest probability of being idle. Alternative approaches exist such as the work by Song et. al. [91] that propose a stochastic channel selection algorithm based on learning automata. The learning automata dynamically adjusts the probability of choosing one channel on the fly and asymptotically converges to the optimal channel, which maximizes the probability of successful transmissions. The learning automata uses historical data on successful transmissions in each channel.

A type of REM can also be used to select channel based on received signal strength from the PUs [88]. This is similar to the used of a fixed deployed sensor network in papers C and D. In the more general case considered in papers F-H, the channel with collective lowest received signal strength received by the CRs from the PUs is selected for operation. The reason for using this is that it is simple and often the default channel selection scheme in standards.

2.2.3 Spectrum Sharing

Spectrum sharing in the spectrum management framework is often considered at the MAC layer. However, the coexistence of the CR users with the PUs adds additional challenges compared to traditional networks and MAC protocols. The spectrum sharing can at least be classified into four aspects [22]. The first classification addresses whether the spectrum sharing architecture is centralized, i.e. controlled by a central entity, or distributed, i.e. based on local policies performed by each CR user separately. In the centralized approach, the central entity is often the base station responsible for spectrum sharing between the CR users or networks. As noted in the thesis scope in Section 1.4, we focus on the centralized approach. The spectrum sharing between CR users served by a centralized base station is mainly addressed by the MAC layer in the standards studied in this thesis. For instance, a modified version of the IEEE 802.16 standard [52] with a CR implementation is considered in papers C and D and an implementation of the IEEE 802.22 standard in papers F-I. The centralized unit can also be a spectrum broker [92–95] as studied in Paper B. Alternatively, protocols using spectrum trading [96, 97] can be used to lease spectrum to CR users or networks.

The second classification addresses the spectrum allocation behavior. The first is cooperative spectrum sharing where the CR users share information about PU appearance and interference measurements when allocating spectrum. This can typically be done through a centralized unit or fusion method. Alternatively, the spectrum allocation behavior can be non-cooperative where the CR users only consider their own measurements when allocating spectrum. Cooperative spectrum sharing is typically used in centralized networks. Non-cooperative is typically used in decentralized networks such as ad-hoc networks. The scope of this thesis, which considers centralized networks, is on the cooperative spectrum sharing method where one spectrum band is allocated for use by all the CR users that cooperate to report information to the base station. In papers C-D, multiple sensors in a fixed sensor network cooperate to detect PUs within the interference range of the CR network. The sensors report these sensing measurements to a centralized fusion center, which further allocates channels to the CR network. This channel allocation is based on allowed interference limits to the primary network. In papers F-I, the CR users cooperate by detecting available channels that can be used by all the CR users in the network.

In the third classification, spectrum sharing can be classified according to the access method as overlay or underlay, i.e. OSA or UWB. The OSA approach, which is overlay, is the main scope of this thesis. To allow secondary operation in the OSA approach, the CR users might be restricted to comply to given interference limits [98–101] as used in papers C and D. Such interference limits might be set by the regulator or the primary spectrum holder.

Fourth, spectrum sharing in this thesis focuses on intra-network spectrum sharing with the main issue of not causing interference to the primary network. The other type of spectrum sharing, which not is the scope of this thesis, is subject to inter-network spectrum sharing where multiple CR networks are operating in the same region.

2.2.4 Spectrum Mobility

Spectrum mobility is related to the fact that the CR user changes its operating channel due to PU appearance or increased interference from PUs. This introduces a new type of handoff in wireless networks. Furthermore, the CR network must adapt to the new channel parameters of the selected channel. The purpose of the spectrum mobility management in CR networks is to ensure smooth and fast transition leading to minimum performance degradation during a spectrum handoff [22]. One important aspect of this spectrum management task is that different protocol layers in the communication stack should adapt to the channel parameters when the CR network switches channel, e.g. to increased latency. This also indicates the importance of a cross-layer design approach. An interesting study by Jihoon et. al. [102] finds that, due to channel switching overhead when a PU appears on the channel, it might be better to stay idle and buffer instead of switching channel to obtain highest throughput. Advanced spectrum mobility aspects are not addressed in this thesis, but simple channel switching is implemented in the simulation models in papers C-D and F-I.

2.3 Sensor Network Aided Cognitive Radio

A sensor network aided cognitive radio (SENDORA) network uses the concept of a wireless sensor network (WSN) that assists a CR network by providing information about the current primary spectrum occupancy. A WSN, not necessarily embedded in the CRs, can be deployed to detect these spectrum holes and report to the secondary system as proposed in the EU FP7 project SENDORA [24, 25]. Input on real time spectrum monitoring by using a separate low cost WSN was recently also requested by FCC [103, point 50]. The

SENDORA concept is studied in papers B-E.

The SENDORA scenario depicted in Fig. 2.4 constitute of three main networks; the primary (usually licensed) network, the secondary network and the WSN. In this scenario, the network of CR users, called the secondary network, exchange information with the WSN. The WSN monitors the spectrum usage, and is thus aware of the spectrum holes that are currently available and can potentially be exploited by the secondary network. This information is provided back to the secondary network then able to communicate without causing harmful interference to the primary network.

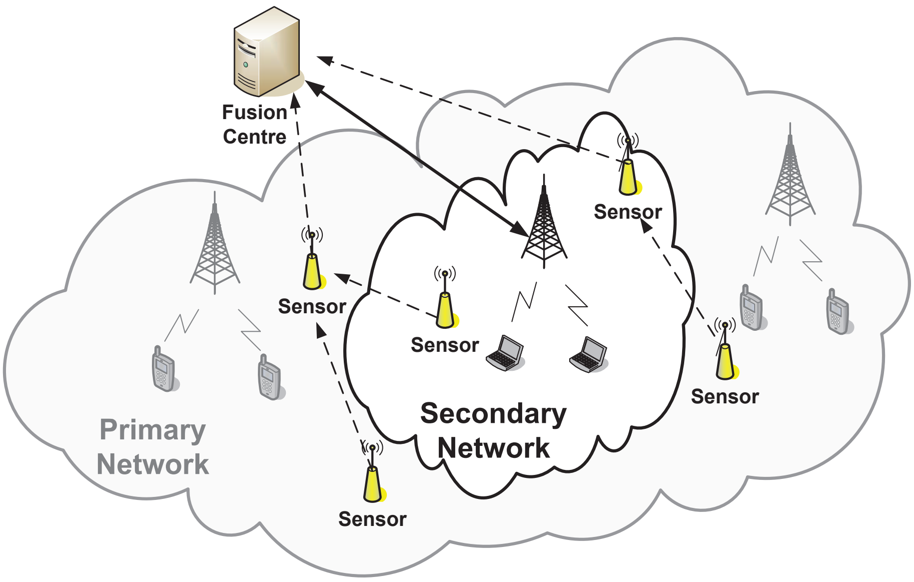


Figure 2.4: General SENDORA scenario.

The CR system architecture consists of three parts: the (secondary) CR communication architecture, the sensing architecture (sensors) and the fusion center which connects the communication and sensing architecture. In papers C and D, we implement a simulation model in NS-2 including the secondary CR network, WSN, fusion center and primary network.

In papers B-D, the CR communication architecture consist of base stations and CR terminals. In Paper E it consists of a LTE network with base stations, cognitive femtocells and CR terminals. However, other type of CR networks such as ad-hoc networks are considered for use with the SENDORA concept [24], but is left out of the scope of this thesis.

The fusion center is a functional entity that receives sensing data collected through the WSN and estimates the spectrum usage situation in the area covered by the WSN. The fusion center also communicates with the CR communication network providing it with the information it needs to operate cognitively in an optimal way.

The sensing architecture consists of a fixed network of sensors complemented with sensing capabilities integrated in some or all of the base stations, cognitive femtocells and CR terminals. The number and positions of the terminals will be uncertain such that a WSN formed by terminals only cannot guarantee detection confidence. A fixed deployed WSN with sensors at selected locations can give more predictable detection confidence. A fixed deployed WSN also has the advantage that the sensors can communicate with each other and eventually with the fusion center through a wired backbone network. Sensors can be powered from the mains. On the other hand, sensing integrated in the terminals will be co-located with the CRs and hence be capable of providing accurate local information to better protect PUs located close to the terminal. To determine the number of fixed sensors that should be deployed, it is necessary to find the required fixed sensor density. The network dimensioning in papers B-E is based on input from Fodor et. al. [104] using their model to derive the required fixed sensor density. Another important topic for SENDORA networks is the protocol design for the WSN to minimize delay for delivering channel availability results, thus maximizing the portion of time the CR network can exploit available channels [105]. Protocol design in the WSN is left out of the scope of this thesis.

2.4 Regulation and Standardization on Cognitive Radio

While CR is developing in research, regulations on CR are also developing. At the same time, standards are emerging that implements CR technologies that confirm to the regulations.

The major activities on regulation for CR technologies and OSA as of today (2013) are on TVWS, which is considered in papers E-I. TVWS are the unused spectrum resources in the temporal and spatial dimensions in the UHF band spanning from 54 to 698 MHz. This is motivated by the fact that there are many unused channels in the TV bands [106, 107] and that it is possible to predict the available TVWS both by using spectrum sensing and geo-location databases [7]. The PUs in the TV bands are mainly the TV broadcasters and wireless microphones. Regulations on TVWS are especially being developed by the Federal Communications Commission (FCC) in the US [14, 108], the Office of Communications (Ofcom) in the UK [15] and the Electronic Communications Committee (ECC) of the Conference of European Post and Telecommunications (CEPT) in Europe [16].

Naturally, as regulations currently are opening for CR in TVWS, the major standardization organizations also focus on developing standards for CR access in TVWS [11]. At current, there are six notable standardization activities on CR focusing more or less on TVWS; IEEE 802.22 [36], IEEE 802.11af [109], ECMA 392 [110], IETF PAWS (Protocol to Access White Space database) [111], ETSI RRS (Reconfigurable Radio Systems) [33, 112, 113] and IEEE DySPAN-SC (Dynamic Spectrum Access Network Standards Committee) [34, 114]. IEEE 802.22 is a standard for Wireless Regional Area Network (WRAN) in TVWS. IEEE

802.11af defines modifications to both the 802.11 PHY and MAC layers to meet the regulatory requirements for channel access and coexistence in the TVWS. This will be very similar to the much used WiFi technology for Wireless Local Area Networks (WLAN), but with cognitive functionality such as sensing and access to a geo-location database. IETF PAWS specifies the use cases, requirements, the mechanism for discovering a white space database, the method for accessing a white space database, and the query and response formats for interacting with a white space database. ECMA 392 has standardized a CR system for TVWS similar to WiFi. ETSI RRS carry out standardization activities related to reconfigurable radio systems encompassing both software-defined radio and CR. ETSI RRS is also working on a standard for TVWS. Also important for CR standardization is the IEEE DySPAN-SC with the objective to develop standards supporting new technologies for next-generation radio and advanced spectrum management. Their scope include DSA radio systems and networks with the focus on improved use of spectrum, new techniques and methods of DSA including the management of radio transmission interference, and coordination of wireless technologies including network management and information sharing amongst networks deploying different wireless technologies.

Mobile operators follow wireless network standardization activities closely and are constantly evaluating the performance of standards in order to decide on which standards to use. Therefore, in papers F-I we evaluate the performance of the first CR standard IEEE 802.22 for operation in the TVWS. In Paper E, we consider a business case scenario for CR networks operating in TVWS, but using cognitive femtocells based on the LTE standard. In papers A, C and D, we add cognitive functionality to the IEEE 802.16 standard. In the following we give more details on the regulations for TVWS and on the specification of the IEEE 802.22 standard.

2.4.1 Regulations on TV White Spaces

The rules on TVWS being developed by the FCC, Ofcom and ECC are quite similar in most aspects. Hence, below we give an overview of the final rules on TVWS by FCC published in September 2010 [14], which as of today are the most complete ones.

The main requirement is that the white space device (WSD) should prevent interference to the primary devices such as TV broadcasters and wireless microphones. The primarily method to achieve this is to use geo-location in the WSD combined with access to a spectrum database. This database contains information about all licensed users, their operating frequencies, locations, areas of operation, and operating schedules. The WSD will then need to access this database to obtain an available channel for use and the allowed transmit power levels. In case the WSD cannot access the spectrum database itself, it must get the required information from a master WSD with access to the database. Another method to protect PUs is to use spectrum sensing.

FCC defines four WSD classes; fixed, portable mode II, portable mode I and sensing only devices. A fixed device, such as a base station, is located at a specific location and is permitted to use 4 W effective isotropic radiated power (EIRP), allowing a maximum transmit power of 1 W and antenna gain 6 dBi. Due to this relatively high transmit power limit, the fixed device is not allowed to operate in channels where one of the adjacent channels are occupied by a PU.

A portable device, such as a laptop or handset, uses lower power and is allowed to transmit with 100 mW. There is a limitation that portable devices only can operate in frequency bands 512 to 608 MHz and 614 to 698 MHz. A portable device is allowed to transmit when adjacent channels are occupied, but must then reduce transmit power to 40 mW. A mode II device is a master device with geo-location capability and access to a database. A mode I device does not have these capabilities and might be called a "slave" device that gets the required information from the master device to access TVWS. An example of this is that a WLAN access point is a mode II device with geo-location capability and access to a database, while the WLAN clients are mode I devices.

A sensing only device uses spectrum sensing to detect the PUs and is required to detect TV signals (ATSC digital and NTSC analog) down to -114 dBm and wireless microphones signals down to -107 dBm. A sensing only device is allowed to transmit with maximum 50 mW.

2.4.2 The IEEE 802.22 Standard

The IEEE 802.22 [36] standard, initiated in 2004 and completed in June 2011, is the first technical standard to provide a WRAN broadband service by operating in the TVWS [42, 115, 116]. IEEE 802.22 devices use geo-location and communicate with a database [7] to obtain information about available frequencies and allowed transmit power levels at their locations. In addition the IEEE 802.22 system can use sensing techniques to detect sudden appearances of PUs, such as TV transmitters and wireless microphones. The IEEE 802.22 system considers a point-to-multipoint network with a base station and a set of CR users with customer premises equipment (CPE).

The IEEE 802.22 standard is based on, and is therefore very similar, to the IEEE 802.16 standard [52]. Both standards use OFDMA and time division duplex (TDD). The first main difference is that the system profiles are different since the IEEE 802.22 standard operates in the UHF bands with 6, 7 or 8 MHz bandwidth profiles dependent on the region it is used in, i.e. in America, Asia or Europe respectively. Furthermore, among some of the main parameters, it uses 2048 subcarriers, linear burst allocation, 10 ms OFDMA frame size and dynamic spectrum sharing for self-coexistence. In Paper F, we give a comprehensive comparison of the parameters used in the two standards.

The second difference from IEEE 802.16 is that cognitive functionality has been added in the spectrum manager of IEEE 802.22. The main task of the spectrum manager is to select the TV channel to be used and to protect PUs of the TV band. It uses the spectrum sensing function, the geo-location function and the spectrum database to decide on the channel to use and the allowed EIRP level. The spectrum manager specifies the set of channel lists, i.e. the backup, candidate and protected channel lists. In the IEEE 802.22 standard a channel will originally get status as backup channel when sensed as unused every six seconds over a period of 30 seconds. In the CPE, the spectrum automaton is a lightweight version of the spectrum manager in the BS. It is mainly responsible for reporting to the BS and for sensing at initial CPE power on, when not connected to the base station and during idle times when there are no tasks pending.

The primary TV broadcasters update the spectrum database with their frequency usage and transmit power levels at all locations when required. Other low power devices operating in these bands, such as wireless microphones, might update the database, but might also appear suddenly without notification. Detection and protection of these wireless microphones is considered to be a great challenge. One approach to handle this is to use sensing technologies to detect wireless microphones and then cease transmission and switch to a vacant TV channel. FCC [14] has allocated two "safe harbor" channels, which can be used by the wireless microphones without registering in the spectrum database. However, spectrum sensing could still be used to increase spectrum utilization significantly in these channels. It is also an open question what other regulators will do to protect wireless microphones. In papers F-I, we study the IEEE 802.22 standard with focus on system level performance and sensing functionality to detect unregistered wireless microphones as the PUs appearing at random or periodic locations and times. Another approach to protect wireless microphones is specified in the IEEE 802.22.1 standard [117]. It uses a beacon, which contains information relevant to the licensed device, including its physical location and estimated duration of TV channel occupancy. The focus in papers F-I is on the sensing approach, whereas the beacon approach is left out of the scope.

Spectrum sensing is an optional feature in the standard. It is used to detect PUs in the frequency band to decide whether the channel is available or occupied. IEEE 802.22 is designed to sense each TV channel separately for signals from analog TV, digital TV and wireless microphones. These sensing functions should comply with the rules and sensing thresholds specified in Section 2.4.1 above. A survey and evaluation of the spectrum sensing techniques in the IEEE 802.22 standard and requirements for sensing in the TV bands are given by Shellhammer [118]. The spectrum sensing function can first be classified into in-band sensing, that senses the operating channel, and out-of-band sensing, that senses activity on other channels that potentially can be used by the IEEE 802.22 system. Considering the MAC layer sensing strategy, two-stage sensing [36, Sec. 7.21.1] is advocated by IEEE 802.22 and considered in papers F-I. The two-stage consecutive sensing strategy [85] can also be used. These MAC layer sensing strategies were described in Section 2.2.1 above.

To the best of our knowledge, there exist no real life field trials nor any comprehensive system level studies of a complete IEEE 802.22 implementation. There exist no performance evaluations with the complete system protocol stack of the IEEE 802.22 standard with sensing functionality. This is the focus of papers F-I.

2.4.3 Other Suitable Spectrum Bands for Cognitive Radio

As noted, in theory, all bands that are underutilized could potentially be subject for CR under the OSA approach. However, different primary systems operating in different spectrum bands have different characteristics. Furthermore, as studied by Weiss et. al. [26,31], different context awareness approaches with varying degree of complexity and maturity are suitable for bands with different characteristics. This is one of the reasons why CR under the OSA approach initially is being regulated for the TVWS with static characteristics. However, CR under the OSA approach might also be used in other spectrum bands with other characteristics as technology matures.

FCC also proposes to make available 100 MHz of shared spectrum in the 3.5 GHz band, currently used for military and satellite operations, using small cells and database technologies [17]. The proposal envisions three tiers of users, each with different levels of rights and protections. The first tier, incumbent access, will be protected from all other users. This would include authorized federal users and grandfathered fixed satellite service licensees. The second tier, protected access, would include critical use facilities, such as hospitals, utilities, government facilities, and public safety entities. These would be afforded quality assured access to a portion of the band in certain designated locations. The third tier, general authorized access, would include all other users that would have the ability to operate subject to protections for the first two tiers. In another notice, FCC also proposes to make up to 195 MHz of additional spectrum in the 5 GHz band available for unlicensed WiFi devices [119]. This proposal also involves the use of geo-location databases and spectrum sensing.

Other bands have been assessed for CR. Spectrum sharing requirements of secondary access to the 960-1215 MHz band, which is primarily allocated to aeronautical usage, is investigated in [120].

Interference within the operating band used by the CR network is not the only challenge. CR networks will also generate interference in adjacent channels [121], which should be considered when deploying CR in white spaces. An example of this is the Lightsquared LTE network, which wanted to deploy a LTE network operating in the band 1525-1559 MHz. This band is nearby that being used by the global positioning system (GPS), 1559-1610 MHz. FCC initially granted Lightsquared a conditionally waiver for building the LTE network [122], but measurements showed that interference degraded the performance of the GPS receivers. Hence, FCC later bared the Lightsquared LTE network.

Another regulatory licensing framework that is being proposed is the licensed shared access (LSA) concept [123], also referred to as authorized shared access (ASA) [124]. This concept allows for licensed sharing of underutilized spectrum by a limited number of rights holders, in incumbents bands, through an individual authorization scheme. It is applicable to any spectrum band with underutilized capacity that can be shared in time and geography. A key feature is to ensure a predictable QoS for all spectrum rights of use holders, network operators and for consumers. The more stable the incumbent spectrum holder's use, the better predictability there is for the QoS of the LSA licensees. Since LSA will share spectrum dynamically considering pre-defined conditions, it could take advantage of CR technologies such as geo-location databases complemented, if necessary, by sensing [125]. This will allow spectrum sharing in frequency, geography and time. However, in the case of the incumbent imposing restrictions, a system for updating, maintaining and providing the access conditions would first need to be established. ETSI RRS is describing a mobile broadband service in the 2.3-2.4 GHz under the LSA regime, which currently is allocated to mobile services.

In papers A, C and D, we focus on CR under the OSA approach in spectrum bands used by the IEEE 802.16 standard, e.g. around 2 GHz. In Paper A, the focus is on CR access in the temporal dimension and in papers C-D the focus is on the spatial dimension. CR access in the temporal dimension becomes more complex when the spectrum usage by the primary user is characterized as temporal fast periodic with potentially stochastic time durations such as in the IEEE 802.16 network with varying traffic load (Paper A), as compared to temporal static such as in the TV broadcasting network or temporal periodic as in the rotating antenna radar bands [26]. Mobile primary users, as considered in papers C and D, also introduce a more stochastic characterization of spectrum usage in the spatial dimension. CR access to spectrum bands with more complex characteristics could be simpler to realize with the LSA approach and the establishment of an individual authorization scheme. It could then also be possible for the primary and secondary operators to cooperate as is found to be important in Paper A.

Spectrum trading has been and is being considered in a range of bands in different countries worldwide, with the UK regulator Ofcom being at the forefront. Two different types of transfers are allowed by Ofcom that enable licensees (spectrum holders) to trade and share rights to use spectrum. First, outright transfer in which all rights and obligations of a license transfer from one party to another. Second, concurrent transfer in which the transferred rights and obligations become rights and obligations of the transferee (buyer or leaser) while continuing, concurrently, to be rights and obligations of the actor making the transfer (seller or lessee). Furthermore, Ofcom allows both a total transfer in which the whole license is transferred and a partial transfer in which only some rights and obligations of the license is transferred. Relating to the spectrum management classification presented in Fig. 2.1 above, this use of spectrum trading will be under the spectrum property rights approach. Spectrum trading was limited to certain bands, but a notice of proposals [126] by Ofcom was recently published to extend spectrum trading to mobile and cellular bands (900 MHz, 1.8 GHz and 2.1 GHz). Some research also exist that aims to enable spectrum-micro trading to buy and sell spectrum resources on a smaller scale than has currently been used in one or more of the spatial, temporal and frequency dimensions [127]. This would enable wireless service providers to acquire spectrum for small or wide geographical areas, for short or long time periods and for narrow or wide bandwidths.

2.5 Business Aspects of Cognitive Radio

The economics of CR under the OSA approach is mainly concerned with the high cost of radio spectrum, where CR can get access to spectrum at lower costs or for free. Mobile operators often use financial modeling to analyse business case and to predict viability of business models. This is the focus in papers B and E. In this section, we give some background and related work on business modeling, economic scenarios for CR, the cost related to obtaining spectrum information, and finally a discussion about the disruptive potential of CR.

2.5.1 Business Modeling

A central part of the business case analysis is to design the business model, which describes the rationale of how an organization creates, delivers, and captures value [128]. Business case analysis uses financial modeling to evaluate the cash flow for scenarios to see how the business model evolves over time. This includes profitability analysis and sensitivity analysis of certain variables in the business model.

In the literature, there exist many different methodologies and frameworks for designing and analyzing business models [128–130]. In papers B and E we use the steps in the theoretically grounded framework for designing and analyzing business models by Ballon [130], since it is fitted for mobile systems and services. This framework follows a multi-parameter approach by defining four levels on which business models operate. First, the value network level consist in identifying actors, their relationships and the value adding roles they provide in the marketplace. Second, the functional architecture level consist in identifying ways to implement the technological architecture, the modules and interfaces between modules, distribution of intelligence in the system, and the inter-operability with other systems. Third, the financial level consist in analyzing the cash flow using revenues and costs for setting up and running the system using the technology. Finally, the value proposition level consist in identifying the value being added to end-users of the system, including questions on how to position the service or product vis-a-vis existing services or products. Kelkar et. al. [29] use the framework developed by Ballon [130] to outline a business framework to evaluate the business impact of DSA technology in cognitive networks. The work in papers B and E are complementary to this work by proposing specific business case scenarios, their ecosystem and the evaluation of CR networks based on the SENDORA concept.

The interlinked technical and economic issues associated with markets for DSA-based wireless services are examined by Chapin and Lehr [9]. A set of potential new entities are identified, such as spectrum use registries and spectrum distributors, as well as product features such as "black boxes", permitting post-interference analysis, and leases that may play important roles in facilitating the growth of the market for DSA-based services. The spectrum broker entity matching buyers and sellers of spectrum is also discussed. They note that research on how these entities and features can work is just as important as research on basic questions of safety in DSA for the technology to fulfill its promise of significant increases in overall spectrum-use efficiency and thereby deliver its full potential for social and economic benefits. In Paper B, we give an overview of potential actors and their roles involved in potential ecosystems for CR networks with focus on the SENDORA concept.

Other than getting access to more spectrum, there are mainly two alternative options to increase capacity; to reduce cell size and to increase spectrum efficiency. It is stated by Chapin [30] that the future for high quality mobile broadband competition will require significantly more sharing among commercial mobile radio service operators of both infrastructure and spectrum, and that a key driver to achieve this is the need to shrink cell sizes that will support efficient spatial reuse of spectrum and lower power operation. In Paper E, we present a business case where cognitive femtocells based on the LTE standard can use TVWS spectrum for free, provide small cells and support many users by using CR.

The concept of telecommunications value-chain is used by Nolan et. al. [28] to study how value can migrate and be created in CR networks. Furthermore, they analyze a business case where CR devices are used as relays to increase coverage and give coverage to devices out of base station range. To the best of our knowledge, this is the only business case study for CR networks that appeared before our studies in papers B and E. Recent business case studies have appeared as described in the following.

A high level assessment of the business viability of cellular use of white spaces for mobile broadband services and promising business scenarios are studied by Markendahl et. al. [131]. First, it is concluded that low frequency bands should be used by mobile operators for wide area coverage and high frequency resources by wireless local area operators. Regarding mobile operators, the promising business scenario is to use TVWS and re-use of existing sites in order to delay or replace deployment of a denser network. These findings confirm the results in papers B-E that infrastructure is one of the most critical parameters to obtain a viable business case. Furthermore, they argue that mobile operators use white space spectrum only in countries with very high spectrum prices. Finally, they also argue to use white spaces spectrum for indoor systems provided by local or mobile operators where mobile operators provide a service platform for business. In another work, Markendahl et. al. [132] study the business feasibility of mobile broadband using TVWS using capacity-cost analysis. This analysis show that market entrants will be in a more difficult position than established actors since a new operator needs to invest in a new infrastructure with sites and transmission. This also confirms the results presented in papers B, that the business case of a new entrant was the most challenging to make viable. It is also concluded in [132] that if spectrum costs are high, the use of TVWS is more cost efficient for both existing and new operators.

A business case for a CR based solution for increasing capacity of LTE networks by using TVWS is evaluated by Grøndalen et. al. [133] and compared to acquiring a license through an auction of spectrum in the digital dividend 2 (698-790 MHz). It is found that the CR option is the best solution, and that investments are more evenly distributed over the study period since there is no initial cost for buying a spectrum license. It is emphasized that determining the best solution depends heavily on the price the operator has to pay for a spectrum license, which also confirm to [132] discussed above. The most cost sensitive parameter is found to be the price of cognitive LTE terminals.

Another business case study presented by the EU FP7 project COGEU [134] considers three different LTE network deployments. A greenfield deployment with only one carrier, either 2.6 GHz or 700 MHz, and a deployment with a legacy carrier of 2.6 GHz additionally with TVWS. It is shown that the network is clearly more profitable when deployed with only the frequency of 700 MHz, with a NPV of 144 M€, while when deployed with 2.6 GHz and TVWS it reaches the NPV value of 132 M€ and for 2.6 GHz the NPV is only 64 M€. In sensitivity analysis, the NPV is more sensible to the variations in the ARPU, fiber costs, and customer base, while it is less sensible to device subsidies, device prices and price of spectrum. Interestingly, these results differ from the finding in [133], where the price of the cognitive LTE terminal was the most sensitive parameter. It should be noted that the scenarios are similar, but different. Also, there are different assumptions in the two studies. One important difference is that TVWS spectrum is free in [133], whereas a spectrum market for TVWS spectrum is considered in [134].

Business cases for rural broadband and for Machine-to-Machine (M2M) communication in TVWS is evaluated by McKenzie et. al. [135]. The most critical parameters for both business case scenarios are found to be the number of customers and the average revenue per customer. These findings can indicate that performance metrics important to support QoS, such as throughput and delay, in the rural broadband case are important for the customer to be willing to subscribe to the service and pay a satisfactory subscription fee. Hence, these findings are motivating the research in papers F-I on performance evaluation of the IEEE 802.22 standard, which is suitable for services such as rural broadband.

2.5.2 Economic Scenarios for Cognitive Radio

Barrie et. al. [54] argue that many contexts in which CR technologies may be applied are so distinct from a business and regulatory point of view, that any conclusions concerning the characteristics and viability of one use case cannot be inferred from the analysis of another. It is therefore essential to establish which parameters are critical for distinguishing fundamentally different economic scenarios. Barrie et. al. [54] define four economical scenarios for CR using three of the business parameters defined as illustrated in Fig 2.5. Here, the main differentiator is the ownership which leads to an unlicensed scenario if not owned by any organization (e.g. ISM bands). If licensed, the spectrum ownership business parameter specifies whether the spectrum band is exclusively assigned to a licensee. If not, the spectrum bands can be grouped into a spectrum pool and made available for sharing by multiple licensees [136]. If the license is exclusive and it is allowed to change ownership of the license, the license is tradable in a market scenario. A license can then be traded for economic compensation [21, 127]. They note that secondary use of spectrum without compensating and interfering with the primary user can be foreseen in this economic scenario, which would confirm to the OSA approach as studied in papers B and E. In this case the spectrum trade is dynamic as opposed to permanent. Finally, if change of ownership is not allowed, the frequency band is restricted to the licensee itself. The licensee might then use CR to e.g. improve resource usage internally [137]. A fourth differentiating business parameter, neutrality, is not used in the taxonomy presented. This would have impacted each of the bottom scenarios allowing a single or multiple different access technologies. Barrie et. al. [54] further analysis the regulatory requirements and the technologies for enabling CR; spectrum sensing, spectrum databases and the cognitive pilot channel (CPC) [77]. It is concluded that geo-location databases is the most preferred solution, although spectrum sensing should not be discarded for potential situations such as highly sensitive applications in high density radio environments. It is also argued that stakeholders involved and system costs should be considered when deciding on which CR enabling technology to use.

In another work, Barrie et. al. [138] classifies business scenarios for spectrum sensing by differentiating on the business parameters for the spectrum license; ownership, exclusivity, tradability, and neutrality. It is concluded that, since different business scenarios have different actors, roles and consequences, the proposed scenarios are fundamentally distinct and incompatible. Hence, every scenario should be analyzed separately to evaluate its viability and the way spectrum sensing can contribute to this.

Medeisis and Delaere [139] present four high level scenarios for the future development of CR as an innovative business proposition. Intuitive logics as a methodology is used for constructing the four equally probable scenarios in a matrix at the intersection of two major uncertainties, the cost and complexity of CR technology and the emergence of viable CR

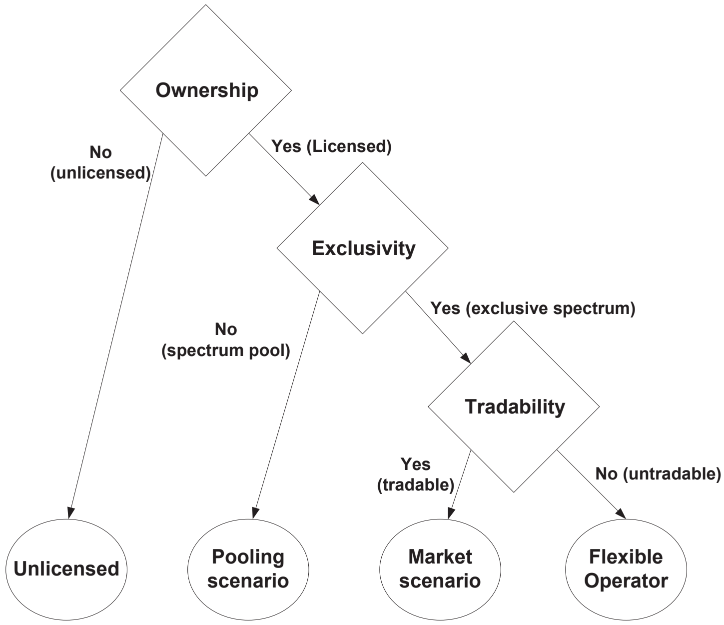


Figure 2.5: Classification of economic scenarios for CR [54, Fig. 3].

business cases. They further state that in the scenario representing the current status quo in the industry (2011), neither viable business cases exists, nor is the CR technology really implementable in any commercially affordable equipment. The business cases proposed and evaluated in this thesis consider deployment of CR networks at a later point in time when the technology can be expected to exist, starting in 2015 in Paper B and in 2017 in Paper E.

2.5.3 Cost of Obtaining Spectrum Information

For CR networks, there is a cost related to obtaining information about available spectrum. Weiss et. al. [31] show that operating context matters when it comes to choosing an appropriate technology for context awareness. Furthermore, they show that solutions based on databases or cooperative sharing with explicit communication between primary and secondary users are the most suitable approaches in static environments such as TVWS. They also show that external sensor networks is the least cost effective. Papers B and E addresses the cost of obtaining information about spectrum usage through the use of externally deployed sensor networks. The fact that spectrum sensing is the least cost effective context awareness approach made it more challenging to obtain viable business cases. We note that sensing might be required by the regulator in some markets to e.g. reliably detect PUs such as wireless microphones in the TVWS. Spectrum sensing can also be used by the secondary operator to control the interference generated and can thereby free more white space spectrum as decisions are based on actual measurements instead of predictions.

2.5.4 Cognitive Radio as a Potential Enabler for Disruptive Innovation

It is often stated that CR is a disruptive technology. However, to the best of the authors knowledge, there does not exist any detailed studies using disruptive innovation theory to analyze the disruptive potential of CR. The objective of this thesis is not to give a detailed study whether CR is a disruptive innovation or not, but to consider CR as a technology with the potential to enable disruptive innovation to opportunistically get access to white space spectrum at low cost or for free. The following gives a brief background on disruptive innovation theory and discuss some examples on how CR can have the potential to enable sustaining and disruptive innovation.

The disruptive innovation theory, as defined by Christensen [51, 140, 141], points to situations in which new organizations can use relatively simple, convenient, low-cost innovations to create growth and triumph over powerful incumbents. The theory holds that existing companies have a high probability of beating entrant attackers when the contest is about sustaining innovations. But, Christensen [141] states, sustaining attackers almost always loose to attackers armed with disruptive innovations. Disruptive innovations are considered to underperform compared to current products used by the mainstream customers. However, the new product might perform better on an alternative dimension, e.g. lower cost or easier to use, and thus open up a new market that the current market does not expect. Over time, the disruptive innovation improves until it is preferred by the mainstream customers. Therefore, incumbent firms often fail to recognize disruptive innovations and the threat they pose. The disruptive innovation theory and framework aims to help managers in recognizing disruptive innovations [141].

Sustaining innovations are what moves companies along established improvement trajectories. They are improvements to existing products on dimensions historically valued by customers. Some examples are computers that process faster and cellular phone batteries that last longer.

Disruptive innovation introduces a new value proposition. They either create new markets or reshape existing markets. There are two types of disruptive innovations [51]; low-end and new-market disruptions. Low-end disruptions can occur when existing products and services are "too good" and hence overpriced relative to the value existing customers can use. These disruptions take place at the low end of the original or mainstream value network. Examples are discount retailers and steel minimills, which both began by offering existing customers a low-priced, relatively straightforward product. New-market disruptions can occur when characteristics of existing products limit the number of potential consumers or force consumption to take place in inconvenient, centralized settings. New-market disruptions are said to compete with "nonconsumption". Examples of new-market disruptions are the personal computer and Sony's first battery-powered transistor pocket radio, since their initial customers were new consumers [51].

Disruptive technology is often seen as a synonym of disruptive innovation. Technologies might be disruptive themselves. However, the term disruptive innovation is preferred since market disruption is usually not created by the technology itself, but by the application of the technology and its business model that disrupts the market. Therefore, for CR, it is important to study the business model in which it is applied in addition to its technological features and performance. It is also important to study the business case of CR when used as a disruptive innovation, but it should be noted that disruption is difficult to predict. Hence, the business case will be difficult to predict.

Yu et. al. [142] notes that what contains a real disruptive innovation observes examination through different lenses. They further clarify three potential misunderstandings of disruptive innovation. First, disruption is a relative phenomenon in that an innovation might be disruptive to one company, but not to a company with another business model. Second, disruptive innovation does not always imply that start-up businesses will replace the incumbents or traditional business, since incumbents with existing high-end technologies can still survive by concentrating on how to satisfy its most demanding but least price-sensitive customers. Third, disruptive innovation is not equal to destructive innovation. A technological innovation that has superior performance in key dimensions with a relatively low-cost structure would directly invade the mainstream market. This can then cause more serious destructive effects than a normal disruptive innovation that focuses on low cost but initially lower performance.

In the following we will discuss some potential low-end, high-end and sustaining innovations for the use of CR.

Potential Low-end Innovation with Cognitive Radio

When mobile operators offer mobile broadband services using emerging technologies such as LTE, they usually first invest in a licensed spectrum band that tends to be expensive. These services offer high capacity and support QoS. One important notice is that such new technologies enable the operator to support more customers and offer higher aggregate throughput. However, these new services might also be “too good” for most customers considering that few customers are using very high throughput applications and that few customers require strict QoS. For CR technologies, the aggregate throughput supported might be equally high and even higher most of the time. On the contrary it might also vary dependent on spectrum availability at given times and locations. Also, the QoS supported by CR technologies considering performance metrics such as delay, throughput and loss rate might be challenging to guarantee due to varying spectrum availability and appearance of PUs. But, by using CR to opportunistically access whitespace spectrum for low costs or for free, a secondary operator will be able to offer broadband services at a lower subscription fee. This might be attractive for many subscribers not willing to pay the subscription fee for strictly stable QoS guarantees, but that are willing to accept a service with generally high throughput and potentially more variable QoS at a lower subscription fee. In this case, the CR operator will gain a new set of customers, which can have the potential to enable low-end disruption.

In Paper B, we study two business cases that have the potential to be disruptive low-end innovations as presented here. First a business case for a joint venture that uses CR for spectrum sharing and second for a new entrant using CR to access white space spectrum. Though, we note that the business case calculations presented in Paper B and Paper E do not consider disruptive effects since these are challenging to predict and quantify. This would also include calculation of competitors' performance.

There is a notable difference of introducing such a service for an incumbent and a new entrant in the market. A new entrant will have the potential to gain a set of new customers and increase market share. However, for an incumbent operator, the CR service will probably gain from its existing customer base and hence cannibalize its own business. This will reduce profits per customer since the subscription fee will be lower than before. On the other side, the incumbent operator also has the potential to gain customers from its competitors in the market. Hence, profit might be higher over time as compared not to introducing the CR service. So, even if the disruptive innovation is found, incumbents are often reluctant to take advantage of it. This is mainly because it would involve competing with their existing technological approach and since the customers are considered less profitable. Therefore, considering that CR technologies might emerge in the market, it will be important for the incumbent operator to understand and consider such a service in the market.

An alternative for the incumbent operator, as recommended by Chirstensen [51, 140], is to spin-off a new business unit offering such a disruptive CR service. While doing this, the incumbent will have the potential to focus on its core services and markets.

Another important difference is that the incumbent operator often owns existing infrastructure that can be used when deploying CR networks. It is shown in Paper B, that the number of new base station sites that has to be established is one of the most critical parameters for a new entrant when deploying CR networks. This makes it challenging to obtain a positive business case for a new entrant.

Much of the research on CR is addressing the problem of providing QoS in CR networks. This is the main objective in the EU FP7 project QoSMOS [143] in addition to providing mobility. Considering that CR networks will evolve and eventually have the potential to provide better QoS and mobility, CR networks will have the potential to provide services with similar, or even better, performance than wireless networks using a static assigned license. Hence, services provided by CR networks will have the potential to disrupt services provided by wireless networks using a narrower and static license.

Potential New-market Innovation with Cognitive Radio

It has been noted that several spectrum bands are underutilized. Hence operators and other organizations hold spectrum licenses that can be used by others. An entity referred to as the spectrum broker has been proposed in e.g. [92–95] that can arrange transactions of the rights to use spectrum licenses between sellers and buyers of spectrum. In Paper B we discuss and briefly address the business case of a spectrum broker, as an entity that deploys, builds and operates a sensor network to sell either sensing information or information on spectrum opportunities to one or more CR operators.

A more advanced spectrum broker adds value by aggregating and partitioning spectrum access rights [9]. The spectrum broker could also enter into contracts with the secondary operators to deliver QoS differentiated spectrum access, while acquiring the rights through contracts with primary operators. This could possibly also involve transfer of given interference limits [144]. In Paper D, we study the technical performance and capacity when allowing different requirements for the maximum interference generated by the secondary to the primary network. A centralized fusion center is used to calculate the interference limits and allocate spectrum rights to the CR network. This fusion center could be considered a similar entity as the spectrum broker, but trading functionality is not implemented in Paper D.

For an operator that holds underutilized spectrum resources, the opportunity to sell the spectrum rights of these spectrum resources to other spectrum users can be a potential source of revenue. Optimally, for the operator, this would be by selling to spectrum users not offering competing services. CR is not necessarily required, but will be important since a CR is flexible. First, the CR has the capability to switch between and use many different frequencies. Second, the CR has sensing functionality that can be used to identify spectrum to be sold or bought through the spectrum broker and to monitor interference. The operator could either be administrating the spectrum broker itself, or sell the rights to use spectrum through the spectrum broker administrated by a third party. If the operator administrates the spectrum broker itself, it would avoid additional costs required by a third party. Alternatively, the operator could spin-off a new business unit for the spectrum broker as recommended by Chirstensen [51, 140]. The introduction of a spectrum broker can have the potential as a disruptive new-market innovation, since it enables a market that does not exist for transferring rights of use of already licensed spectrum. This could enable operators, which can not afford spectrum in traditional auctions held by regulators, to get access to spectrum. The government would then no longer have monopoly for selling rights to use spectrum through traditional spectrum auctions held by regulators. As noted in Section 2.4.3, regulators have started to facilitate such secondary spectrum trading.

A second business scenario for CR with potential to enable new-market disruption is the opportunity to offer sensing as a service [145]. This would involve detecting and selling of information about spectrum holes and usage. The spectrum information could either be sold directly to secondary operators or to a central entity such as the spectrum broker. For best possible performance, this should be done by having a separate wireless sensor network, possibly enhanced by sensors embedded in CR terminals. The actor administrating the sensor network could be a single or multiple operators, the same actor that administrates the spectrum broker as considered in the "spectrum broker" business case (Paper B) or a third party. Operators deploying CR technologies might need to deploy an external sensor network[3] and could then also have the opportunity to offer sensing as a service. This would enable a new market for the sale of spectrum information, which can be used by secondary operators to access unused spectrum. A potential competing service might be a spectrum database if existing or possible to deploy, but a wireless sensor network can have the possibility to monitor interference and provide more accurate information about spectrum usage.

The spectrum broker and sensing as a service scenarios are also interesting in that these potentially new-market innovations further can enable low-end disruption, since operators then can acquire spectrum at potentially lower cost. Hence, these operators can offer lower priced services competing with incumbents over less demanding customers as described above.

Potential Sustaining Innovation with Cognitive Radio

As noted, spectrum costs are a major expense in the operator's value-chain to provide telecommunication services. Spectrum is also a limited resource. By getting access to more spectrum, the operator can increase performance, support more users and support better QoS in existing offered services. Again, we consider that CR technologies can get spectrum for free or at lower costs, but that the performance and QoS supported will be less predictable. To cope with the increasing capacity demand, the spectrum scarcity and the expensive spectrum license costs, the operator can deploy CR technologies such as base stations and femtocells to offload its mobile network. If the performance for metrics necessary to support QoS for the CR network degrades at a given time and location, the operator can handover the customers that require strict QoS to its existing macro network that is able to support strict QoS. In this case, operators using CR technologies are able to reduce costs and offer services to its customers with similar QoS support, or Quality of Experience (QoE) considering the customer's experience of the service [146], as compared to its competitors not using CR that have to acquire additional spectrum at higher costs. An alternative way of seeing it, is that operators using CR will be able to offer better

[3] It was considered that operators deploy an external sensor network themselves for the business cases studies "spectrum sharing" in Paper B and "cognitive femtocell" in Paper E. However, the studies consider that the operator uses the sensing information themselves only. Potential additional revenue that could be obtained from selling information about spectrum usage and interference is not calculated.

services to its customers when compared to its competitors that are not using CR and cannot acquire additional spectrum. According to Christensen [51], this can be considered a sustaining innovation. In Paper E, we study a business case of the sustaining innovation where cognitive femotcells are used to offload the macro LTE network.

2.6 Scenarios for Cognitive Radio

The chosen scenario in the EU FP7 project SENDORA is CR based on nomadic broadband in urban and suburban areas [56], as studied in papers B-D. This scenario targets non real-time services since it is difficult to give strict QoS guarantees with CR. However, it can be possible to offer real time services if the spectrum conditions allow it. The service is considered to offer both high bit rates and low costs. The scenario is attractive for a mobile operator, since it can be used to offload the mobile network while considering that the mobility feature will only be required for a small percentage of the users. This is because the users will usually be stationary when using the mobile broadband service.

Six scenarios are evaluated to have a high potential by MacKenzie et. al. [58,147], in the EU FP7 project QoSMOS. Each scenario is evaluated using a questionnaire to score the scenario based on three criteria; the QoSMOS benefit (i.e. could a QoSMOS scenario be better than a conventional system?), the benefit for actors, the requirement for managed QoS, and mobility. The selected scenarios are dynamic backhaul, cellular extension in whitespaces as studied in Paper I, rural broadband as studied in papers F-H, cognitive ad-hoc network, direct terminal-to-terminal in cellular, and cognitive femtocell as studied in Paper E.

Fitch et. al. [148] describe three use cases for operation in TVWS and model their technical feasibility; future home networks, coverage of the street from inside buildings, and broadband access to rural and underserved premises. Furthermore, these use cases are classified into the scenarios; indoor services, outdoor coverage from indoor, and outdoor services. It is concluded that the first use case will be fixed point-to-point links such as rural broadband access as studied in papers F-H, which is forecasted to occur in the next one to two years (2011). Looking ahead, the use-cases will become more mobile and with variable and managed QoS, such as indoor to outdoor coverage via super WiFi community networks and possibly femtocells as studied in Paper E. It is also concluded that mobile network operators are interested in the use of TVWS for cellular extension and rural access as studied in Paper I. However, they note that there are challenges to be overcome such as provision of reliable service and managed mobility and QoS [143], agreement across US and Europe on regulatory aspects, CR equipment certification procedures, development of a new value chain including databases, and over-the-top services based on location.

Sayrac et. al. [137] present the wireless network operator's approach to CR systems specific for International Mobile Telecommunications (IMT) systems. It is stated that, as for today (2012), there is no yet enough information to assess possible future business benefits of the CR system deployment scenarios in IMT systems, except the intra-operator scenarios. This is because the introduction and deployment of CR systems in other scenarios still require further studies on the technical and operational issues to determine their impact and evaluate possible benefits. The main objective in intra-operator scenarios is to increase spectrum efficiency with primary usage of CR, contrary to the secondary usage such as with the OSA model in TVWS. A concept referred to as radio environment maps (REMs) is presented that collects and intelligently processes geo-localized measurements in IMT systems. This further constitutes a cognitive enabler that allows the mobile network operator to achieve the potential improvement promised by CR through the environment awareness that it provides. The objective of this thesis is not on intra-operator scenarios for CR, but on the objective to find technical and business benefits for a mobile operator using CR under the OSA approach. The conclusions in this thesis also differ, but this is mainly because we consider studies on longer terms than in [137].

A brief overview of the scenarios considered in this thesis is given in Table 2.1. All papers

Table 2.1: Overview of scenarios studied in this thesis.

Paper	A	B	C,D	E	F,G,H	I
General Scenario Parameters						
Scenario	Cellular Broadband based on CR					
Mobility level	Mobile	Nomadic	Nomadic	Mobile	Static	Mobile
Spectrum (GHz)	2.0	0.5-3.5	2.0	TVWS	TVWS	TVWS
Range (km)	1.0	0.5,1	0.575, 0.767,1.15	0.075, 0.1	1.0	1.0
Traffic	CBR, FTP	N/A	CBR	N/A	CBR,VoIP, Video	CBR
QoS	BE	BE	BE	BE	BE,UGS	BE
Environment	Outdoor sub/urban	Outdoor sub/urban	Outdoor sub/urban	Indoor-Out urban	Outdoor suburban	Outdoor suburban
CR Specific Scenario Parameters						
Context awareness	N/A	WSN, CR	WSN, CR	WSN, CR	CR, Database	CR, Database
Architecture	BS	BS, FC	BS, FC	Femtocell, FC	BS,	BS
Primary users	IEEE 802.16	All	IEEE 802.16	TV,WM	WM	WM
Standard used in CR network	IEEE 802.16	N/A	IEEE 802.16	LTE	IEEE 802.22	IEEE 802.22

consider the cellular broadband scenario with base station (BS) or cognitive femtocell and CR terminals. In Paper A, we focus on the 2 GHz band. In papers B-E, we use the SENDORA approach with a fixed wireless sensor network (WSN) combined with sensing in the CR terminals. The WSN reports sensing results to a fusion center (FC) responsible for allocating spectrum and allowed transmit power based on interference limits. In papers B-D, the focus is on nomadic services in urban and suburban areas [56], in the 0.5-3.5 GHz (Paper B) and 2 GHz (papers C and D) bands. In paper E, the focus is on the cognitive femtocell scenario [147] in TVWS to offload the macro LTE network. In papers F-I, we focus on the CR standard IEEE 802.22 in suburban areas using TVWS. We consider this similar to the rural broadband case. The context awareness approach used is sensing in both the base station and CR terminals to detect wireless microphones (WMs) combined with geo-location databases having information about spectrum usage by TV broadcasters. In papers F-H we consider fixed customer premises equipment (CPE) and in Paper I we consider mobile CR terminals. In all papers, we focus on scenarios with the constant bit rate (CBR) data application using the best effort (BE) QoS profile. In Paper F, we also study the VoIP and video applications using the unsolicited grant service (UGS), i.e. guaranteed bit rate, and the BE QoS profiles respectively. More details on each scenario are given in each of the respective papers.

Chapter 3

Contributions of Papers

In this chapter we give a summary of each of the papers A-I in this thesis in separate sections. Each paper summary contains a summary, related work, and main the contributions. Before summarizing each paper, we briefly describe the progression in this thesis work and the papers as illustrated in Fig. 1.4 in Chapter 1.

The research started with Paper A, where we study the spectrum occupancy and available capacity for CR access in the temporal domain in primary OFDMA systems.

In papers B-E, the focus is on the performance of the SENDORA concept, both from a technical and economic perspective. In Paper B, we propose and evaluate three business cases and identify the most critical parameters for each of them. One critical parameter found is that the establishment of new base station sites should be minimized. It was found that the business case gets negative if more than 6% new base station sites must be established. This triggered the technical simulation study in Paper C on performance and capacity for different cell sizes in a SENDORA network. It was found that a high reuse of existing base station sites is challenging, which points in the direction of smaller cells such as femtocells. This first led to, in Paper D, a performance study on how relaxed requirements for the maximum interference generated by the CRs can be used to obtain full reuse of existing base stations. Then, paper E proposes and evaluates a new business case based on cognitive femtocells motivated by findings in Paper C.

The studies in papers F-I focus on performance evaluation of the first cognitive radio standard IEEE 802.22 with spectrum sensing functionality and wireless microphones as primary users. In Paper F, we evaluate the performance of different sensing strategies for multimedia traffic with different QoS profiles. In Paper G, we evaluate the effect of spatiotemporal wireless microphone activity on the performance of the IEEE 802.22 network with spectrum sensing considered. In Paper H, the focus is on delay analysis in IEEE 802.22 in addition to an analytical model that enables evaluation of opportunistic spectrum OFDMA (OS-OFDMA) networks. Finally, in Paper I, we propose, implement and evaluate three spectrum selection functions that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection in the IEEE 802.22 simulation model.

The author of this thesis has been the main responsible for the studies in the papers where he is the first author. This includes proposing most of the ideas, implementing the simulation models, running the simulations, analyzing the results and writing the papers. In Paper B, he was active in proposing and evaluating the business cases, determining assumptions and responsible for writing the paper, but he was not responsible for the actual modeling. In Paper H, he was responsible for the delay analysis and implementing the NS-2 simulation model, but he was not responsible for the analytical modelling and definition of the OS-OFDMA model where he was active in discussions.

3.1 Paper A

Towards Dynamic Spectrum Access in Primary OFDMA Systems

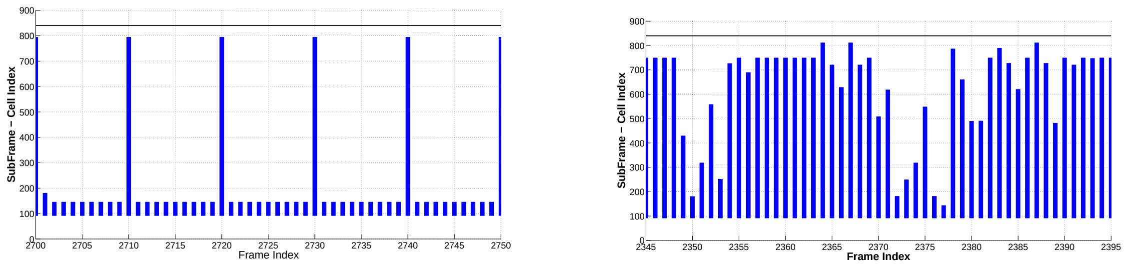
P. Grønsund, H.N. Pham and P.E. Engelstad, "Towards Dynamic Spectrum Access in Primary OFDMA Systems", in Proc. 20th IEEE Personal, Indoor and Mobile Radio Communications Symposium (IEEE PIMRC), Tokyo, Japan, Sep. 13-16, 2009

Summary

Orthogonal Frequency Division Multiple Access (OFDMA) is the major transmission technology in the future mobile wireless broadband systems, and is already used in Mobile WiMAX and LTE. Therefore, it is interesting to study how DSA technologies such as CR under the OSA approach could be used to access unused spectrum in primary OFDMA systems. This knowledge is useful for CR and other technologies for DSA that aim at improving the overall spectrum usage. In this paper, we use a system level simulation model for the IEEE 802.22 standard based on OFDMA to characterize the distribution of the spectrum occupancy over time and calculate the available capacity for various network scenarios and traffic models.

The analysis concludes that it should be possible to utilize white spaces in a primary OFDMA network. It is shown that the OFDMA scheduling technique and the traffic models used by PUs will have significant impact on the characterization of spectrum occupancy. As an example, Fig. 3.1 illustrates the difference in spectrum occupancy for different traffic models. In Fig. 3.1(a), the 5 PUs receiving 20 packets per second of 1500 bytes per packet occupies 24% of the total spectrum on average. In Fig. 3.1(a), the 3 PUs downloading a file occupies 81.65% on average. The spectrum occupancy can be characterized as temporal

fast periodic with short durations [26]. These short durations are found to be stochastic depending on the characteristics of the PU traffic model and load. This is evident in Fig. 3.1 by observing the difference in occupancy in consecutive OFDMA frames for the different PU traffic model scenarios. Hence, it might be more challenging for a CR system to utilize white spaces in primary OFDMA systems, as compared to a CR system that aims to use white spaces with more static characteristics such as in the TV white spaces. Therefore, it is concluded that cooperation and assistance from the primary operator is important to maximize the secondary system utilization of the available OFDMA capacity. A complete secondary system could use a combined approach, where the DSA scheme is based on statistics about OFDMA occupancy, cooperation with the primary operator and combined with sensing techniques to detect PUs in real time to reduce the probability of interference.



(a) 5 PUs receiving constant bit rate (CBR) traffic. (b) 3 PUs receiving files using file transfer protocol (FTP).

Figure 3.1: Downlink OFDMA occupancy in primary OFDMA network (x-axis shows consecutive OFDMA frame indexes in the time dimension, y-axis shows usage of OFDMA slots).

Related Work

Geirhofer et. al. [23] present a statistical model for spectrum idle times using a semi-Markov model and its use to derive access strategies. The primary system is a WLAN system based on Orthogonal Frequency Division Multiplexing (OFDM), which spectrum usage is characterized. The temporal characteristics and spectrum occupancy differs in the OFDM and the OFDMA systems as studied in Paper A, which mainly is because different MAC protocols are used. To the best of our knowledge, the characterization of spectrum use and available capacity for CR in the temporal dimension in primary OFDMA networks has not been studied before.

Work on spectrum characterization appearing after our work is given by Weiss et. al. [26]. They characterize spectrum usage for a cell site using the LTE standard, which is based on OFDMA and is a similar technology to IEEE 802.16, as temporal fast periodic and spatial static. However, in our more detailed characterization of OFDMA networks presented in Paper A, we show that the fast periodic time period in IEEE 802.16 has a temporal stochastic characteristic depending on the characteristics of the PU traffic model and load. Interestingly, they also suggest the need for cooperation in such primary systems as was concluded in Paper A.

We also refer to Paper 1 appearing under other publications not included in this thesis. Paper 1 builds on the ideas and characterization presented in Paper A by proposing and modeling a scheme that allows an unlicensed CR system to statistically and opportunistically access the whole spectrum bandwidth during the last consecutive symbols of each primary OFDMA subframe.

Contributions

The main contribution of this paper is the characterization of spectrum availability for CR access in the temporal domain to unused spectrum in a primary OFDMA network. Available capacity is calculated and the distribution of the spectrum occupancy is analyzed over time for various network scenarios and traffic models. It is shown that spectrum availability depends on the PU traffic model. This is illustrated by 5 PUs receiving constant bit rate traffic with 20 packets of 1500 Bytes per second that occupies 24% versus 3 PUs downloading a file using FTP that occupies 81.65% of the total spectrum on average. We also give a discussion on how to design a secondary CR system to utilize the available capacity based on the characterization of spectrum availability. This is a new contribution that is of highest importance when considering CR access in idle time periods in spectrum held by primary OFDMA networks and to increase overall spectrum usage.

3.2 Paper B

Evaluation of Business Cases for a CR Network based on Wireless Sensor Network

O. Grøndalen, M. Lähteenoja and P. Grønsund, “Evaluation of Business Cases for a Cognitive Radio Network based on Wireless Sensor Network”, in Proc. 5th IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (IEEE DySPAN), Aachen, Germany, May 3-6, 2011.

Summary

In this paper[1], we propose and evaluate three business case scenarios for deployment of a sensor network aided cognitive radio (SENDORA) system in a typical European city. These are entitled "spectrum sharing", "spectrum broker" and "new entrant". Cash flow analysis is used to evaluate the economic viability of these business cases. Furthermore, we use sensitivity analysis to find the input parameters that are most critical to obtain a viable business case. We also give an overview and analysis of the ecosystem for SENDORA systems.

The first and main business case is based on spectrum sharing, where several spectrum owners establish a joint venture. This joint venture gets the rights to use the unused spectrum resources of all those spectrum owners in a cognitive way. A nomadic broadband service is offered using the SENDORA system. It is found that the spectrum sharing business case is one of the best possible cases for the studied system because the joint venture operator has free access to vacant frequency resources of the mother companies, detailed knowledge of the primary systems and good possibilities for sharing infrastructure with the owning operators. However, the studied system is an innovative concept and some of the assumed parameters are therefore uncertain. Therefore, the most important value from the business case calculations is to identify critical aspects influencing the profitability so that future research and development work can focus on them. It is found that the most critical aspects as illustrated in Table 3.1 are the fixed sensor density, the fixed sensor operational expenditures (OPEX) and the number of new cognitive base station sites required. It can be seen that the business case get negative if the fixed sensor density is higher than 72 sensors/km^2, if the fixed sensor operational costs is higher than 17.5 €, or if more than 6% new base station sites must be established. A high number of sensors that increase the costs considerably are required dependent on the interference limit used. This will be important to consider by regulators and spectrum owners when deciding on allowed interference probability limits. The high sensitivity for the fixed sensor OPEX indicates that it is critical that the fixed sensor power consumption is low and that the mean time between failures is long. The sensitivity of the number of new sites required indicates the importance for the secondary operator to reuse as many existing base station sites as possible. Another critical parameters is the subscription fee, which depends both on the quality of the service offered and on the price level for wireless broadband services in the market. It was found that the business case gets negative with a reduction of only 3% in subscription fee.

The second business case entitled "Spectrum Broker" is based around the concept of a an entity that deploys, builds and operates a sensor network and sells either sensing

[1]Paper B builds on the initial results and analysis presented in Paper 2 appearing under Other Publications not included in this thesis. In Paper B, we present the final results of our work and a more comprehensive description of the business cases, ecosystem and analysis.

Table 3.1: NPV sensitivity analysis for the “Spectrum Sharing” business case (the bold value illustrates the input parameter for the base case).

(a) Fixed sensor density

#fixed sensors per km^2	NPV [M€]
10	11.44
30	7.77
65	**1.36**
72	0
120	-8.72

(b) Fixed sensor OPEX

Fixed sensor OPEX [€]	NPV [M€]
5.0	6.82
10.0	4.09
15.0	**1.36**
17.5	0
20.0	-1.37

(c) Share of new sites

Share of new sites	NPV [M€]
0%	**1.36**
6%	0.00
10%	-0.89
30%	-5.28
50%	-9,67

information or information on spectrum opportunities to one or more CR operators. The main output from this business case is to calculate the costs for the spectrum broker as input to the the third “New Entrant” business case. In this business case scenario, we study the potential of a new entrant using the SENDORA system without existing infrastructure or frequency licenses that rents spectrum from the spectrum broker. It is found that if the new entrant has to pay the spectrum broker what it needs to cover its expenses, the business case gets strongly negative even when these expenses are shared with three other cognitive operators also using information from the spectrum broker. Hence, the new entrant business case scenario is the most challenging to make viable.

Related Work

Nolan et. al. [28] analyze a business case where CR devices are used as relays to increase coverage and give coverage to devices out of base station range. This business case scenario is not directly related to our business cases proposed in Paper B, except that both study business cases for CR networks using the same method. To the best of our knowledge, this is the only business case study for CR networks that appeared before our business case study in Paper B. Hence, the business cases scenarios proposed and evaluated in Paper B have not been addressed before.

Other works on business case and cost analysis that appear after our work in Paper B can be found in [31, 132–135, 149]. Analysis on the cost of obtaining information about available spectrum is presented by Weiss et.al. [31,149]. They conclude that external sensor networks is the least cost effective context awareness approach compared with databases, cooperative sharing and sensing embedded in terminals only. These papers refer to our work in Paper B and builds on some of our assumptions. The use of external sensor networks therefore makes it more challenging to achieve a viable business case compared to using other context awareness approaches. However, we note that external sensor networks, as used in Paper B, might be required by the regulator in some markets to e.g. reliably detect primary users. External sensor networks can also be used by the secondary operator to control the interference generated and can thereby free more white space spectrum as decisions are based on actual measurements instead of predictions. Markendahl et. al. [132] show that when using TVWS spectrum, market entrants will be in a more difficult position than established actors since a new operator needs to invest in a new infrastructure with sites and transmission. This confirms the results in Paper B that the establishment of new BS sites is a critical parameter.

Contributions

The main and completely new contribution in this paper is the proposal and evaluation of three business case scenarios for deployment of SENDORA systems; “spectrum sharing”, “spectrum broker” and “new entrant”. We also analyze and evaluate the ecosystem for the SENDORA system. The viability of the business cases is analyzed and the most critical aspects to obtain viable business cases are identified. It is shown that the most critical aspects are the fixed sensor density, the fixed sensor operational costs and the number of new cognitive base station sites required. The business case gets negative if the fixed sensor density is above 72 sensors/km^2, if the fixed sensor operational costs increases with more than 16%, or if more than 6% new base station sites must be established. These findings are important contributions since they identify the importance to conduct further research on these critical aspects. The study is of high relevance for mobile operators that consider the use of CR, the SENDORA concept and wireless sensor networks.

3.3 Paper C

Comparison of Cell Sizes for Cost Efficient Deployment of a Sensor Network Aided Cognitive Radio System

P. Grønsund and O. Grøndalen, “Comparison of Cell Sizes for Cost Efficient Deployment of a Sensor Network Aided Cognitive Radio System”, Journal of Signal Processing Systems, vol. 69, no. 1, pp. 95-104, Oct. 2012.

Summary

The study in this paper[2] is motivated by the finding in Paper B, that a reuse of existing base station sites is important to achieve a positive business case for a SENDORA system. Therefore, in Paper C we determine the performance and capacity for different cell sizes when considering the costs for deployment of base stations in a secondary CR network

[2]Paper C is an extended version of Paper 3 appearing under Other Publications not included in this thesis.

that exploits spectrum holes identified by the WSN. All parts of the SENDORA system are implemented in a system level simulation model based on the IEEE 802.16 standard. This includes a mobile primary network, a centralized secondary network, a WSN and a centralized fusion center. The WSN uses energy detection to detect signal strength from PUs in the spectrum bands and reports these to the fusion center. The fusion center then determines available channels based on given interference limits. To get a detailed picture of performance, we implement realistic network topologies, traffic models and the whole protocol stack of the secondary and primary systems with actual transport, network, link and physical layers.

First, it is found that equal cell size for the secondary and primary systems with a cellular reuse pattern with seven frequencies is difficult to achieve. Fig. 3.2 shows the average throughput when cell size is set to half (0.575 km), two thirds of (0.767 km) and equal to (1.15 km) the primary cell size. Highest throughput is achieved with transmit power −14 dBW for all units when cell sizes are equal, however in average only about 50% of the secondary users obtain connectivity. The total system capacity is therefore not utilized. Note that this conflicts with the results in the business case analysis in Paper B, where it was found important to have a high reuse of existing base station sites to obtain a viable business case. Second, it is found that a full capacity can be achieved with secondary cell size set to half and two thirds of the primary cell size and with restricted transmit power levels. The number of BSs installed for half the primary cell size will then be quadrupled and at least 75% of these would not be co-located with primary BSs leading to increased costs. This points in the direction of shorter range, smaller and less expensive BSs for the secondary system such as WiFi access points and femtocells. It is also shown that the average CR system throughput decreases when either the transmit power or the number of CR users increases. This is mainly because channel availability decreases since the probability that a PU is within interference range increases when either the transmit power or the number of CR users increases, respectively.

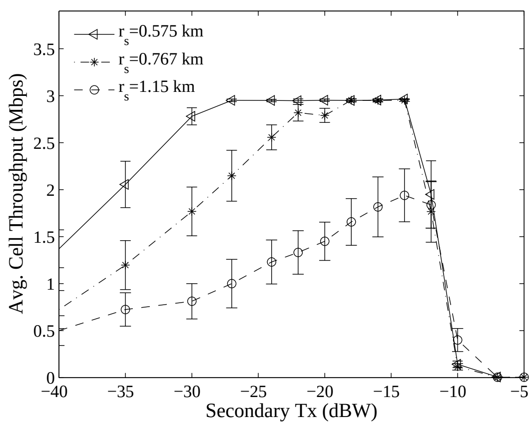


Figure 3.2: Average cell throughput for the secondary CR system with different cell sizes.

Related Work

Axell et. al. [150] and Larsson et. al. [151] study the potential capacity in the spatial dimension for a frequency planned network. They note that obtaining any substantial benefits from opportunistic spatial spectrum reuse in a frequency-planned network without causing substantial interference is going to be very challenging. In conclusion they motivate that CRs cooperate on spectrum measurements, perhaps by forming a sensor network, or that the primary system is made somewhat tolerant to occasional interference from the CRs. This motivates the use of a WSN to increase capacity in the secondary CR network in Paper C. Wang and Chen [101] analyze the capacity of a CR network with average received interference power constraints. They evaluate performance in a CR network consisting of a single cell with multiple CRs and PUs. However, none of these works consider a mobile network for the secondary CR network and they do not consider co-location of secondary and primary base stations as in Paper C. They do assume that the CRs can perfectly judge the distance to the PUs, whereas in Paper C we consider a realistic approach where the WSN estimates the location of the PUs by using sensing results. To the best of our knowledge, the scenario studied in Paper C has not been studied before.

Contributions

The main contribution of this paper is to determine the performance and achievable cell size in a SENDORA system when deployed with base stations co-located with a mobile primary system that uses a cellular reuse pattern with seven frequencies. A detailed system level simulation model is implemented, which enable the performance evaluation of the considered scenario with the complete protocol stack using metrics such as throughput and packet loss at the application layer. A realistic approach is considered where the WSN estimates the location of the PUs by using sensing. It is shown that only 50% of the CR users obtain connectivity when using full co-location. However, it is found that full capacity can be achieved for smaller cell sizes in the CR system such as half and two thirds of the primary cell size. This study is of high importance since it evaluates the performance and capacity for a CR system that opportunistically access spectrum in the spatial dimension in a frequency planned primary network, while reusing existing base station sites for cost efficient deployment of the CR network.

3.4 Paper D

Evaluation of Interference Requirements in a Sensor Aided Cognitive Radio System

P. Grønsund and O. Grøndalen, "Evaluation of Interference Requirements in a Sensor Aided Cognitive Radio System", in Proc. 54th IEEE Global Communications Conference (IEEE GLOBECOM), Houston, Texas, USA, Dec. 3-7, 2011.

Summary

As a solution to the problem of achieving full capacity while having full reuse and co-location of existing base station sites in Paper C, in Paper D we study how relaxed requirements for the maximum interference generated by the secondary CR transmitters to the primary system can improve secondary system performance and capacity. To achieve this, the system level simulation model for the SENDORA system developed in Paper C is extended to include the use of different interference limits for the CR. The WSN is used to detect PUs and report this to the fusion center responsible for determining available channels based on given interference limits.

Fig. 3.3 shows the average cell throughput for different interference requirements for the CR. We show that it is possible to find interference limits for the CR that allow full throughput and coverage for the secondary CR system when co-located with primary base stations. This comes at the cost of a slight reduction in throughput and an increase in packet loss per user of 2% on average for the primary system. We conclude that this can be considered acceptable for a business model where the primary operator gets economic benefits from improved secondary system performance.

Related Work

This paper builds on the system level simulation model implemented in Paper C by implementing the use of different interference limits for the secondary CR network. As noted above, the work in [150, 151] study potential capacity in the spatial dimension for a frequency planned network, but using a different method and a different network topology. They do not consider the use of different interference limits and they do not consider co-location of primary and secondary base stations as in Paper D. To the best of our knowledge, the use of relaxed interference requirements for CR in the considered scenario has not been studied before.

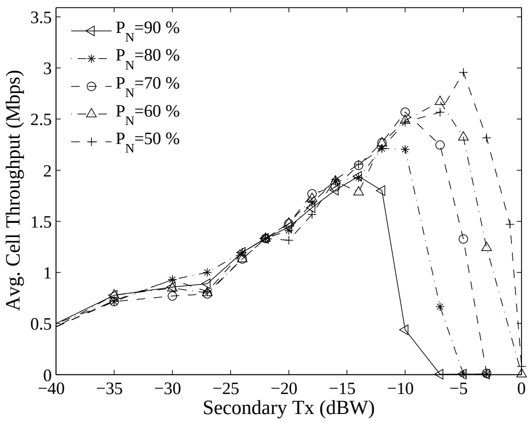


Figure 3.3: Average cell throughput for the secondary CR system with different interference requirements (interference generated to the primary system should correspond to an increase of the noise floor of less than 0.5 dB with a certain probability P_N).

Contributions

The main contribution of this paper is the evaluation of how relaxed requirements for the maximum interference generated by the secondary CR transmitters to the primary system can improve secondary system performance and capacity in a SENDORA system. A detailed system level simulator is implemented and used to evaluate performance with the complete protocol stack of the SENDORA system. We find interference limits that allow full capacity and throughput in the secondary system and evaluate the impact on the performance of the primary system. This study is of high importance since it investigate how the use of relaxed interference requirements for the CR can enable full capacity in a frequency planned primary network, while reusing existing base station sites for cost efficient deployment of the CR network.

3.5 Paper E

Business Case Evaluations of LTE Network Offloading with Cognitive Femtocells

P. Grønsund, O. Grøndalen and M. Lähteenoja, “Business Case Evaluations of LTE Network Offloading with Cognitive Femtocells”, Telecommunications Policy, vol. 37, no. 2-3, pp. 140-153, Mar.-Apr. 2013.

Summary

Mobile networks are increasingly becoming capacity limited such that more base stations and smaller cells or more spectrum are required to serve the subscribers' increasing data usage. Among several challenges, additional spectrum and the establishment of new base station sites become challenging and expensive. This paper study how cognitive femtocells using the SENDORA concept can solve these challenges by considering the economic benefits and challenges through proposing a business case attractive for mobile operators. The study in Paper E builds on the work presented in Paper B by reusing results on sensor network density analysis and some of the results on cost estimation. The novelty of this study is the proposal and evaluation of a completely new business case and scenario. In this business case scenario we study the use of cognitive femtocells that cover outdoor areas from indoor, when aided by a sensor network, to offload the macro network.

The cognitive femtocell strategy is compared with an alternative strategy where an operator deploys conventional femtocells and builds additional base stations to meet the traffic demands. The business case analysis illustrates that there is a potential for cost savings when offloading the mobile network with cognitive femtocells compared to the alternative strategy. It must be emphasized that the studied concept is innovative and that the business case period starts in 2017 (five years from the actual study), hence parameter assumptions are uncertain. Therefore, as the most important message of this work, sensitivity analysis is used to reveal the most critical aspects of the cognitive femtocell business case. The most critical parameter regarding the cognitive femtocell business case is the price for backhauling the cognitive femtocell. Since little information exists about this price, a more detailed study to estimate this price will be of highest importance. It is found that the costs in the two business cases equals if the price for backhaul increases with 64%. It is also found that the number of supported users by a cognitive femtocell is a critical parameter which is important to consider when developing cognitive femtocells. We assume that the cognitive femtocell can support 20 users. The cognitive femtocell business case will be less profitable than the alternative case if the number of users supported by the cognitive femtocell is lower than 15 users. Interestingly, it is found that parameters related to the senor network such as required density, price and OPEX for the fixed sensors are less critical compared to the study in Paper B. The reason for this is that sensors now are embedded in the cognitive femtocells. It is also found, as illustrated in Fig 3.4, that the coverage radius for the cognitive femtocell is important. The optimal radiuses for lowest costs are found to be between 40 and 70 m in the urban area and 80 m in the suburbs. Here, even lower ranges causes more cognitive femtocells to be deployed resulting in much higher costs. Sensitivity analyses are also presented for spectral efficiency, cognitive and conventional femtocell offloading gain, customer density, and price for base station site establishment.

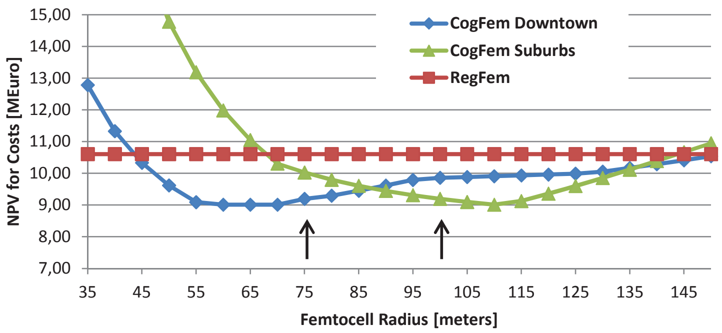


Figure 3.4: Sensitivity analysis of costs for different coverage radius for the cognitive femtocell (CogFem) in downtown and suburbs, compared with the alternative strategy (RegFem). Arrows points to actual values assumed.

Related Work

The use of cognitive femtocells to cover outdoor areas from indoor locations is studied by Kawade and Nekovee [152]. They compare the use of 2.4 GHz, 5 GHz and TVWS spectrum and find that the optimal approach for coverage is to use TVWS. They indicate that for data traffic, community networks operating in TVWS are a viable and significantly less expensive alternative to the cellular operators' next generation network. However, they do not provide detailed cost analysis nor do they consider offloading of mobile networks. Xiang et. al. [153] also demonstrate that cognitive as compared with conventional femtocells can achieve increased capacity, which motivates the study in Paper E. It is shown by Gur et. al. [154] that with better sensing capability, a cognitive femtocell discovers the spectrum opportunities more efficiently and increases throughput while causing less interference to the PUs. This motivates the use of the SENDORA approach with an external WSN, however its high costs should also be considered as found in Paper B. A motivating business case study by Claussen et. al. [155] show that by using conventional femtocells in combination with the macrocellular network, there is potential of significantly reducing total network costs. They do not consider cognitive femtocells. Other positive effects for femtocells not considered in Paper E is the potential to reduce customer churn as shown to be important in a business case study by Signals Research Group [156]. To the best of our knowledge, there exist no works on business case analysis for cognitive femtocells. This is the first time a business case study is presented where cognitive femtocells that cover outdoor areas from indoor, when aided by a sensor network, are used to offload the macro network.

Contributions

The main contribution of this paper is the proposal and evaluation of a completely new business case scenario where cognitive femtocells that cover outdoor areas from indoor, when aided by a sensor network, are used to offload the macro network. This contribution is important since it is the first work that gives a detailed evaluation of the business potential of this scenario. Another important contribution is that we identify the most critical aspects to achieve a viable business case such as the price for backhauling and the number of users supported by the cognitive femtocell. These are important input to further research and to operators that consider the use of the studied scenario.

3.6 Paper F

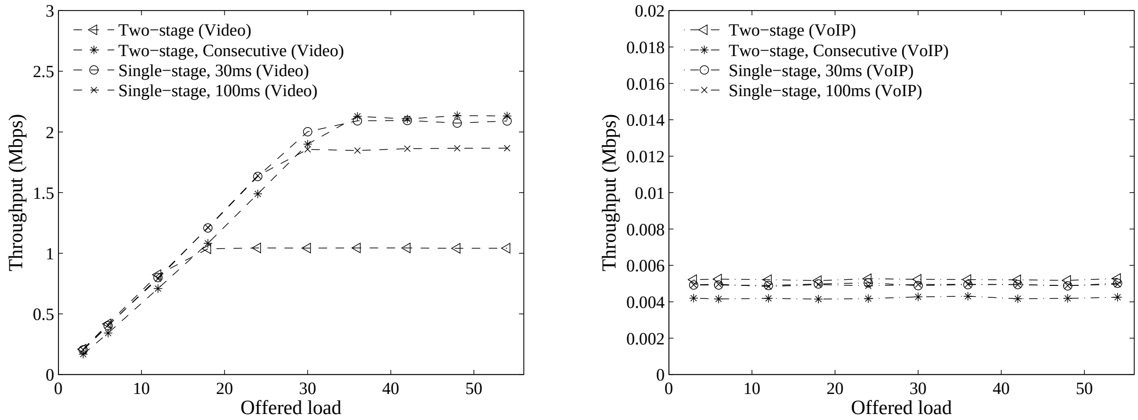
System Level Performance of IEEE 802.22 with Sensing-Based Detection of Wireless Microphones

P. Grønsund, P. Pawełczak, J. Park and D. Čabrić, "System Level Performance of IEEE 802.22 with Sensing-Based Detection of Wireless Microphones", Accepted for publication in IEEE Communications Magazine, 2013.

Summary

In this paper we evaluate the performance of the IEEE 802.22 standard with focus on the effect of spatiotemporal wireless microphone activity on the performance of the IEEE 802.22 network. In order to study the system wide performance of IEEE 802.22, we develop a system level simulation model based on the most complete and up to date IEEE 802.22 standard using the network simulator NS-2. Since the system level simulator is implemented in NS-2, performance of IEEE 802.22 can be measured with exact implementations of the higher layer protocols. The network scenario is limited to one base station and a set of customer premises equipment (CPE). The performance evaluation in this paper considers novel sensing strategies and simultaneous multimedia traffic using different QoS profiles in IEEE 802.22. Four sensing strategies are implemented and evaluated in the simulator; two-stage sensing, two-stage consecutive sensing, single-stage sensing with short sensing duration and single-stage sensing with long sensing duration.

The analysis shows that the performance for different sensing strategies should be considered dependent on the required QoS. This is illustrated in Fig 3.5, which show aggregate throughput for the CPEs receiving video traffic using the best effort QoS profile and VoIP traffic using the guaranteed bit rate QoS profile, when using the different sensing strategies. Among other observations, it can be seen that throughput for two-stage sensing congests since a high number of false alarms causes sensing overhead. It can also be seen that two-stage consecutive sensing achieves highest throughput for high offered load, but lower throughput for low offered load since more packets are lost due to interference. It is also found in Paper F that average delay increases with respect to the overhead caused by the sensing strategy used in the IEEE 802.22 network. Furthermore, it is found that VoIP traffic can be prioritized to achieve lowest possible delay for the specific sensing strategy irrespective of the best effort traffic load. The impact on the wireless microphones is found to be low in general and it is demonstrated that interference is caused only for short intervals when the wireless microphone appears. A tradeoff for the selection of sensing strategy is found between achieving high capacity in the IEEE 802.22 network and protecting the wireless microphones at a highest possible level.



(a) Video Throughput.

(b) VoIP Throughput.

Figure 3.5: Aggregate system throughput for simultaneous video and VoIP transmission: three CPEs receiving video traffic with increasing number of sessions and one CPE receiving VoIP with one session.

Related Work

Many studies on specific components of IEEE 802.22 networks exist, e.g. [37–50]. For example IEEE 802.22 traffic analysis [37], IEEE 802.22 spectrum sensing algorithm design [38], circuit design for IEEE 802.22 spectrum sensing layer [39], IEEE 802.22 physical layer extension with MIMO [40], IEEE 802.22 networks coexistence [41], duplexing schemes [42] and IEEE 802.22 mesh establishment [43]. Kim and Shin [44] discusses the maximization of spectrum opportunities discovery by sensing period adaption and delay minimization in finding a channel. In [45], they discuss sensing period and sensing time optimization to meet the detection requirements while minimizing sensing overhead. Their two-stage sensing approach proposed differs from that in Paper F, because it uses either coarse or fine sensing to minimize sensing overhead while meeting the detection requirements. On the other hand, simulation studies of IEEE 802.22 like [46], consider a limited set of protocol design options. None of the studies consider the complete protocol stack of IEEE 802.22 and the impact of wireless microphones on IEEE 802.22 operation.

The most related work are the evaluation of the IEEE 802.22 MAC layer with the two-stage sensing scheme by Cordeiro et. al. [48–50]. They implement the MAC layer in the OPNET network simulator and evaluate MAC layer throughput, delay and the network resilience. The physical layer with effects such as propagation and interference is not implemented in their simulation model. Wireless microphones as the PUs are not considered. These limitations, however, enable them to run simulations with a higher number of users compared to our study in Paper F. It also seems that probability of detection and false alarm not are considered in their model. Their two-stage sensing scheme differs from that in Paper F. Instead of triggering coarse sensing immediately after a coarse sensing detection as in Paper F, the coarse sensing results are used to decide whether the next fine sensing period should be executed or cancelled. Thus, the two-stage sensing scheme used in Paper F will detect the PU and vacate the channel faster, but has the potential to add more sensing overhead. However, interference to the PU is not presented in [48, 49]. MAC layer throughput and delay results presented in [48] show that using two-stage sensing not impacts the results much. It is shown in Paper F that, when two-stage sensing with a false alarm probability of 10% is used with frequent coarse sensing stages, throughput reduces significantly for higher offered load as the number of users increases. It is also shown that delay increases for two-stage sensing. Another difference is that delay and throughput are measured at the MAC layer in [48–50], whereas delay and throughput are evaluated at the application layer in Paper F. Hence, the instantaneous throughput result in Paper F show similar effects, but differs from that presented in [48, 49]. The evaluation in Paper F also presents details concerning instantaneous interference to the IEEE 802.22 network and to the wireless microphone.

Performance evaluation using Markov analysis by Jeon et. al. [85] show that the proposed two-stage consecutive sensing scheme can increase the maximum channel utilization of CR users, while maintaining the detection delay of PUs under a predefined value. In Paper F, it is found that two-stage consecutive sensing can increase throughput and reduce delay, but that packets loss increases slightly. These higher layer metrics are not evaluated in [85], and the complete protocol of IEEE 802.22 with wireless microphones, different QoS profiles and traffic models are not considered.

Contributions

Paper F implements a highly detailed simulation model with the complete protocol stack of the IEEE 802.22 standard able to evaluate performance at the system level considering metrics such as throughput, packet loss and delay. The simulation model is used to evaluate performance of novel sensing strategies and simultaneous multimedia traffic using QoS profiles with different prioritization in the IEEE 802.22 standard. Wireless microphones are implemented as the primary users. This is a novel contribution since, to the best of our knowledge, this is the first time the complete protocol stack of the IEEE 802.22 standard with sensing functionality to detect presence of wireless microphones has been implemented and used to evaluate performance of sensing strategies and different QoS profiles. The study in Paper F is of high relevance for both the research community and operators when deploying CR standards, when considering which sensing strategy to use and when considering supporting QoS profiles with IEEE 802.22.

3.7 Paper G

System Level Performance of IEEE 802.22 with Sensing-Based Detection of Wireless Microphones

P. Grønsund, P. Pawełczak, J. Park and D. Čabrić, “Sensing of Wireless Microphones in IEEE 802.22: A System Level Performance Evaluation”, Accepted for publication at the IEEE International Conference on Communications (IEEE ICC), 2013.

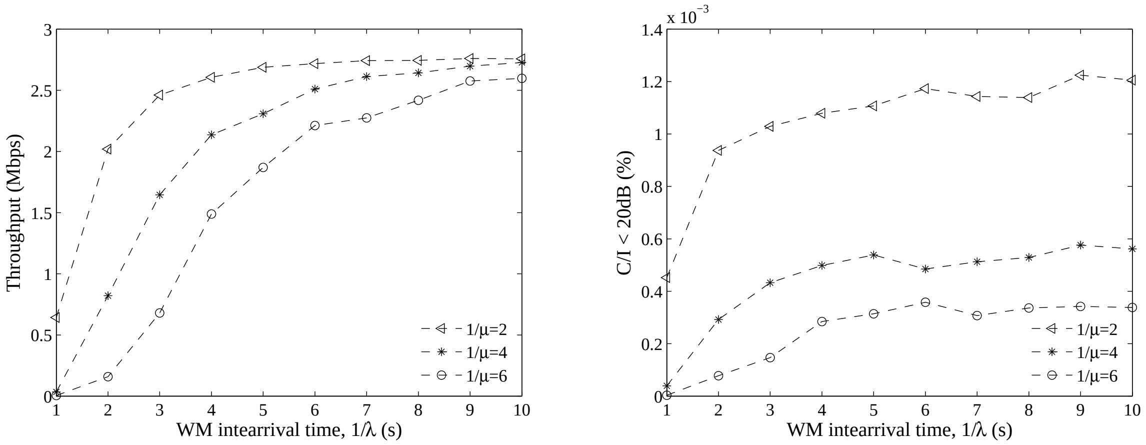
Summary

In this paper, we use the same simulation model for a CR system based on the IEEE 802.22 standard in NS-2 as presented in Paper F. The focus is on evaluating the performance of the IEEE 802.22 standard with sensing functionality, when considering the effect of different activity levels of spatiotemporal wireless microphone activity in channels not occupied by TV broadcasters. Performance of the IEEE 802.22 system is evaluated in terms of throughput, packet loss and interference. The impact on the wireless microphone is also evaluated in terms of interference.

It is found as illustrated in Fig. 3.6(a) that the wireless microphone activity level should be quite high in all channels to reduce IEEE 802.22 throughput. For example, it is found that about 50% wireless microphone occupancy in each of total of four channels is needed to reduce throughput remarkably. The impact on the wireless microphones as given in Fig. 3.6(b) is found to be low in general, when the two-stage spectrum sensing strategy is used with frequent sensing stages.

Related Work

Gosh et. al. [157] implement a spectrum sensing prototype based on energy detection to detect wireless microphones, and demonstrate a 100% detection capability at signal levels down to -115 dBm. There also exist relevant studies on the interference models from the CR to the wireless microphone [158] and on the required exclusion zone from CR to wireless microphone [159]. However, to the best of our knowledge, except from papers F-I there does not exist any evaluation of the impact of wireless microphone operation on system level performance of IEEE 802.22.



(a) Aggregate IEEE 802.22 Throughput. (b) Percentage of time WM C/I $<$ 20 dB.

Figure 3.6: IEEE 802.22 performance for various wireless microphone (WM) inter-arrival time ($1/\lambda_{wm} = 1, \ldots, 10\,\mathrm{s}$) and average on times $1/\mu_{wm} = \{2, 4, 6\}\,\mathrm{s}$.

Contributions

The main contribution of this paper is the performance evaluation of a CR system based on the IEEE 802.22 standard with sensing functionality, when considering the effect of different activity levels of spatiotemporal wireless microphone activity. Performance is evaluated for the IEEE 802.22 system in terms of throughput, packet loss and interference. Impact on the wireless microphone performance is evaluated in terms of interference. This study is highly relevant when deploying CR systems such as based on the IEEE 802.22 standard in scenarios where the density and activity of wireless microphones, or other low power primary users, tend to be high. The study showed that IEEE 802.22 system throughput starts to drop when the wireless microphones occupies more than 50% of the time in each of four channels in the coverage area of the IEEE 802.22 system.

3.8 Paper H

Analysis Framework for Opportunistic Spectrum OFDMA and its Application to IEEE 802.22 Standard

J. Park, P. Pawełczak, P. Grønsund and D. Čabrić, "Analysis Framework for Opportunistic Spectrum OFDMA and its Application to IEEE 802.22 Standard", IEEE Transactions on Vehicular Technology, vol. 61, no. 5, pp. 2271-2293, Jun. 2012.

Summary

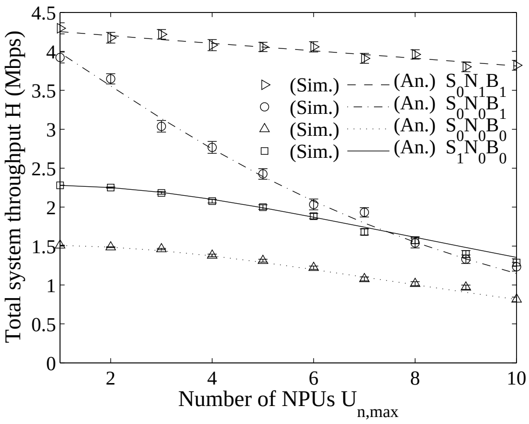
In this paper, we study the performance of the IEEE 802.22 standard with novel features such as sensing strategies, subchannel notching and channel bonding. Two models are used. An analytical model is used to model Opportunistic Spectrum-OFDMA (OS-OFDMA) networks[3]. The simulation model presented in papers F and G is used to evaluate delay for a CR system based on the IEEE 802.22 standard.

The analytical model presented enables evaluation of OS-OFDMA networks using metrics such as blocking probability, or most importantly, throughput. The core feature of the model, based on a discrete time Markov chain, is the consideration of different channel and subchannel allocation strategies under different primary and secondary user types, traffic and priority levels. The analytical model also assesses the impact of different spectrum sensing strategies on the throughput of the OS-OFDMA network. In addition, this model considers studies of co-channel interference. The analysis is applied to the IEEE 802.22 standard, to evaluate the impact of the two-stage spectrum sensing strategy and varying temporal activity of wireless microphones on the system throughput.

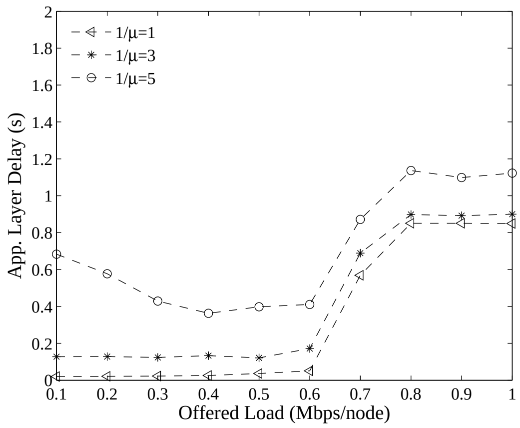
The performance evaluation suggests that OS-OFDMA with subchannel notching and channel bonding could provide almost ten times higher throughput compared with a design without those options, when the activity and density of wireless microphones are high. An example result from Paper H is given in Fig 3.7(a), which show the performance gain when using channel bonding and subchannel notching when the number of wireless microphones increases. Furthermore, it is confirmed that the OS-OFDMA implementation without subchannel notching, as in the IEEE 802.22 standard, is able to support real-time and non-real-time QoS classes, provided that wireless microphone temporal activity is moderate. Also, the two-stage spectrum sensing option improves OS-OFDMA throughput, provided that the length of spectrum sensing at every stage is optimized using the analytical model.

In addition to the analytical model, this paper also presents a set of comprehensive simulation results on delay performance using the IEEE 802.22 NS-2 simulation model. Delay is measured at the application layer, which includes delay on all layers of the TCP/IP protocol stack, and at the MAC layer measuring delay from the packet is transmitted until it is received at the physical layer. Fig. 3.7(b) show that delay at the application layer increases as the wireless microphone activity increases. This is because packets are buffered at the base station due to an increase in the number of channel switches and since the probability of obtaining an available channel reduces. It is also shown that delay dramatically increases when the OFDMA frame is filled with data, which is because packets are being buffered at the base station.

[3]The study using the analytical OS-OFDMA model in Paper H builds on and extends the model introduced in Paper 4 under Other Publications not included in this thesis.



(a) Total throughput for increasing number of wireless microphones (NPU) for different design options where S: two-stage (1) or fine sensing (0), N: subchannel notching used (1) and not used (0), B: channel bonding used (1) and not used (0).



(b) Delay at application layer for increasing traffic load for different wireless microphone on times $1/\mu_n = \{1, 3, 5\}$ and inter-arrival time $1/\lambda_n = 5$. Comparing to the OS-OFDMA model, the NS-2 model uses $S_1 N_0 B_0$.

Figure 3.7: Results in Paper H: (a) total system throughput for OS-OFDMA model and (b) delay with IEEE 802.22 system level simulator.

Related Work

The work closest to the scope of the analytical model can be found in [160] in which an IEEE 802.16 system was evaluated. However, the model developed therein cannot be used directly to evaluate the OS-OFDMA system due to the lack of spectrum sensing and PUs activity features. Another work in [161] analyses system level aspects of subchannel/subcarrier allocation strategies for OS-OFDMA. However, no comparison with the IEEE 802.22 subchannel assignment has been considered. Furthermore, no QoS classes, PU priorities and two-stage spectrum sensing mechanisms were included in the model. A set of relevant papers that analyze performance of MAC protocols for OSA networks include [162–164]. However, none of those works consider OFDMA, usually abstracting the underlying physical channel structure. The studies by Cordeiro et. al. [49, 50] evaluate MAC layer performance with channel bonding in IEEE 802.22. However, they do not consider the presence of different PUs and subchannel notching.

Maharjan et. al. [47] study delay reduction for real-time services in IEEE 802.22 and propose a scheme that reduces delay considering sensing delay. In their scheme, real-time users are allowed to transmit during fine sensing since feature detection is used, while non-real-time users conduct fine sensing. They use analytical modeling and do not consider the complete protocol stack of IEEE 802.22 omitting aspects such as propagation modeling, channel errors and error protection. Cordeiro et. al. [48] study delay at the MAC layer using the OMNET simulator. They find that MAC layer delay for the two-stage sensing scheme not reduces performance considerably compared to single-stage sensing. They do not consider effects on the physical layer and they do not consider impact on delay with appearance of PUs such as wireless microphones. None of the papers consider delay at the application layer in a CR system based on IEEE 802.22 using a complete protocol stack.

Contributions

The first main contribution of this paper is the proposal of an analytical framework to quantitatively assess the performance of a network based on OS-OFDMA, considering features such as channelization structure, subcarrier allocation, resource assignment to network subscribers, different spectrum sensing methods and QoS classes. It is shown that OS-OFDMA with subchannel notching and channel bonding could provide almost ten times higher throughput compared with a design without those options, when the activity and density of wireless microphones are high. These results are important input to regulators considering the use of subchannel notching in the TVWS. The second main contribution of this paper is a set of comprehensive simulation results on delay performance using a highly detailed system level simulation model for the IEEE 802.22 standard. This evaluation is of high relevance when considering the support for delay sensitive applications in CR systems based on standards such as IEEE 802.22.

3.9 Paper I

Spectrum Sensing Aided Long-Term Spectrum Management in Cognitive Radio Networks

P. Grønsund, P.E. Engelstad, P. Pawełczak, O. Grøndalen, P.H. Lehne and D. Čabrić, "Spectrum Sensing Aided Long-Term Spectrum Management in Cognitive Radio Networks", Submitted to IEEE Conference on Local Computer Networks (LCN), Sydney, Australia, Oct. 21-24, 2013.

Summary

Spectrum sensing is commonly used in CR networks to detect PUs of the spectrum and then cease transmission. However, sensing results can also be used to generate statistical knowledge about the spectrum usage. For example, wireless microphones operating in the TV white spaces often appear at specific venues such as schools, concert halls or churches and at specific times such as in the mornings, evenings or on Sundays. Hence, their location and appearance pattern can be predicted from spectrum sensing statistics. Furthermore, this information can be used to enhance performance by selecting a channel with reduced probability of interference from wireless microphones. In this paper, we implement and evaluate three spectrum selection functions that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection in IEEE 802.22, with the goal to enhance performance by reducing interference and increasing throughput. To evaluate performance of the spectrum selection functions, these are implemented in the highly detailed system level simulation model for the CR standard IEEE 802.22 as used in papers F-H. A difference from papers F-H is that the CR users are mobile.

The first spectrum selection function, *SSE-Distance*, is expected to improve performance when the CR terminals are mobile by selecting the channel with the longest expected distance to the wireless microphones. This is motivated by the fact that wireless microphones often appear at specific locations in venues such as schools and churches. The second, *SSE-OnOff*, is expected to improve performance when wireless microphone activity is high by selecting the channel with highest probability of being available. This is motivated by the fact that wireless microphones often appear at specific time intervals such as each morning, evening or Sunday. The third, *SSE-Hybrid* combines the former two to use the optimal SSE function depending on spectrum usage statistics.

Fig. 3.8 shows aggregate throughput for 8 CR users for different wireless microphone activity levels. The proposed spectrum selection functions are compared with a spectrum selection function *SSE-Power*. This function selects channel based on instantaneous sensing results. Thus, not using long-term spectrum usage statistics based on historic, accumulated sensing results. It is found that the spectrum selection function *SSE-OnOff* that uses statistics about channel idle and busy periods performs best when PU activity is high. In this scenario, the throughput gain for *SSE-OnOff* compared to *SSE-Power* is 11.5% for highest PU activity and 1% for the lowest PU activity. It is also found that the *SSE-Distance* function that uses predictions about location and distance to PUs gives highest throughput when CR users are mobile and the PU activity is lower. For example, a maximum throughput gain of 4.7% is obtained for PU inter-arrival time 40 seconds. Finally, we do not always obtain optimal performance for the proposed *SSE-Hybrid* function. However, the overall throughput gain for *SSE-Hybrid* is generally higher than *SSE-Power* with 3.4% on average. Hence, better understanding of *SSE-Hybrid* is considered for a future work. Overall, the proposed spectrum selection functions reduced the harmful interference for both the IEEE 802.22 network and the wireless microphones as the primary users. For the considered scenario, using *SSE-OnOff* reduces the average time the wireless microphone experiences harmful interference with 115% on average for all inter-arrival times compared to using *SSE-Power*. The average time the IEEE 802.22 network experienced SINR less than its modulation and coding threshold reduces from 0.0085% using *SSE-Power* to 0.0007% using *SSE-OnOff* on average for all inter-arrival times. This resulted in a more stable network with lower outage rate for the CR users and the higher system throughput compared to *SSE-Power*.

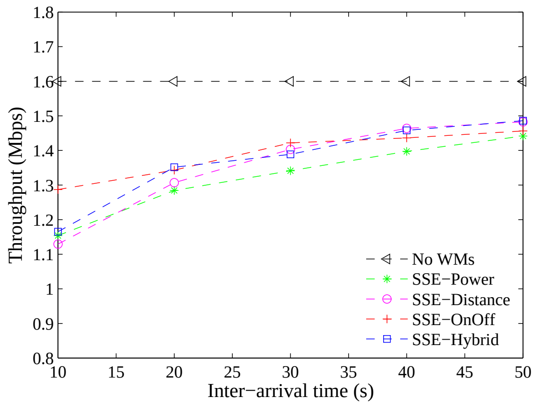


Figure 3.8: Aggregate throughput for 8 CRs for various wireless microphone (WM) activity levels (increasing WM average inter-arrival time means lower WM activity level). WM average on time is selected randomly in the range 2.5 to 7.5 seconds. "No WMs" is the optimal case without presence of WMs. "SSE-Power" selects the channel with lowest received signal strength without considering historical sensing measurements.

Related Work

Similar functions to *SSE-OnOff* are proposed and studied in [87, 165–169] and to *SSE-Distance* are proposed and studied in [170]. Kumar et. al. [165] propose a proactive spectrum access approach similar to *SSE-OnOff* in Paper I, where secondary users utilize past observations to build predictive models on spectrum availability. They show that the proactive approach can significantly reduce the number of disruptions to the CRs. Yang et. al. [166] study a similar approach. They show that the proactive approach effectively reduces the interferences to PUs by up to 30% and significantly decreases instantaneous drops in throughput at the CR. Höyhtyä et. al. [167] propose a simple classification and learning method to detect the pattern type and to gather the needed information for intelligent channel selection in periodic and stochastic ON-OFF patterns. They show that the amount of channel switches needed over time reduces up to 55%. Arshad and Moessner [87] develop a model that characterizes the number of spectrum opportunities available using the probability and approximation theory with an ON-OFF model. Geirhofer et. al. [23] present a statistical model for spectrum idle times using a semi-Markov model and its use to derive access strategies in a primary system based on WLAN. Furthermore, in [168] they introduce a coexistence framework between an ad-hoc OFDM network and an infrastructure network, which based on an ON-OFF continuous-time Markov chain model allocates power and transmission time. Zhao et. al. [169] also model the channel occupancy by the PUs using continuous-time Markov chain and propose a periodic sensing strategy with optimal dynamic spectrum access. Jiang and Weng [170] use trilateration with the maximum likelihood estimation method to estimate the position of PUs, and uses this model to allocate resources. They show that their scheme can enhance transmission rate and reduce outage probability for the CR. The novelty in Paper I is the proposal to use such spectrum selection functions to complement the existing spectrum management framework in IEEE 802.22 with the specific application to wireless microphones as the PUs and their behavior. By implementing the complete protocol stack for a CR system based on IEEE 802.22, we are able to evaluate the performance of these functions complementary to the existing spectrum management framework and spectrum sensing schemes in IEEE 802.22 for several metrics such as throughput, packet loss, delay, and interference to both the IEEE 802.22 system and the wireless microphones. To the best of our knowledge, this has not been done before.

Contributions

The main contribution of this paper is the implementation and evaluation of three spectrum selection functions in IEEE 802.22 that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection, with the goal to enhance performance by reducing interference and increasing throughput. These spectrum selection functions are implemented and evaluated in a highly detailed system level simulation model for the IEEE 802.22 standard. It is shown that the spectrum selection functions can reduce the harmful interference for both the IEEE 802.22 network and the wireless microphones, which results in a more stable network with higher system throughput. This study is important since it illustrates and evaluates how spectrum management functions executed on longer time scales, based on the historical record of existing short-term measurements, can reduce interference and increase throughput by working complementary to the existing short-term spectrum management functions in IEEE 802.22.

Chapter 4

Conclusions

Cognitive Radio (CR) is a promising technology to solve the problem of spectrum scarcity and to increase spectrum efficiency. By using CR technology, with techniques such as spectrum sensing and databases, one is able to obtain information about and utilize white space spectrum. Spectrum costs, which tend to be high for mobile operators, can then be reduced significantly. For mobile operators, CR brings challenges in that the operator might experience both increased interference and competition, but also opportunities in that the operator might benefit from using CR in existing or new networks and markets. The main research objective of this thesis is to study how a mobile operator can benefit from using CR to opportunistically access white spaces, both by evaluating technical performance and economic viability of attractive scenarios. In conclusion, by example case studies, it was shown in this thesis that there are potentials for a mobile operator to use CR to access white spaces and achieve well performing technical and economic viable solutions. These studies and results are important for a mobile operator to understand how to benefit from using CR. Furthermore, CR was considered as having the potential to enable sustaining or disruptive innovation when used to opportunistically access valuable spectrum. We identified potential disruptive innovations when using CR, but it was noticed that CR equally well, or more commonly, can be used by mobile operators to enable sustaining innovation to enhance performance and capacity in existing networks as valued by customers.

Our main findings, which will be summarized in more detail below, are highlighted as follows:

- By characterizing spectrum usage and analyzing potential capacity in primary OFDMA networks, we showed that there is a potential for CR systems to utilize white spaces.
- We found that one of the most promising business cases for an operator using a sensor network aided CR system is that of a joint venture that gets the rights to use the "unused" spectrum resources of spectrum owners. The most business critical parameters were found to be the fixed sensor density, the fixed sensor OPEX and the number of new base station sites required.

- By using technical simulations we found that high reuse of existing base station sites is difficult to achieve, which points in the direction of shorter range and less expensive access points such as femtocells.
- However, we found that full reuse of base station sites can be achieved by relaxing interference requirements for the CR to the primary network.
- We showed that a promising business case is to use cognitive femtocells aided by a sensor network to offload the LTE network. The most business critical parameters were found to be the price for backhauling the cognitive femtocell and the number of supported users by the cognitive femtocell.
- We evaluated performance of a CR system based on the IEEE 802.22 standard with spectrum sensing and found that the activity of wireless microphones as the primary users should be quite high to reduce throughput and delay.
- Interference from IEEE 802.22 devices to the wireless microphone was found to be low in general and to occur only for short periods when using novel sensing strategies.
- We showed that the guaranteed bit rate QoS service for VoIP can be prioritized in IEEE 802.22, though the sensing strategy is important to satisfy strict QoS requirements for throughput and delay.
- We showed that spectrum selection functions that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection can enhance performance in IEEE 802.22.

In the following we give a summary of the research while highlighting the main scientific contributions in bold font, as well as discussing limitations of the research and proposing directions for future work.

4.1 Summary of the Research and Scientific Contributions

4.1.1 Opportunities for Cognitive Radio Access in Primary OFDMA Systems

As a first step in this thesis, the potential performance gains and spectrum availability were characterized for CR access to unused spectrum in a primary OFDMA network. Furthermore, the available capacity was calculated and the distribution of the spectrum occupancy was analyzed over time for various network scenarios and traffic models. The analysis concluded that **it is possible to utilize white spaces in spectrum held by a primary mobile OFDMA system, but that the OFDMA scheduling technique**

and the traffic models used by the primary users will have significant impact on the characteristics of spectrum occupancy. This was illustrated by 5 primary users receiving constant bit rate traffic with 20 packets of 1500 Bytes per second that occupies 24% versus 3 primary users downloading a file using FTP that occupies 81.65% of the total spectrum on average. It was also shown that the occupancy in consecutive OFDMA frames varies for different primary user traffic model scenarios. It should be noted that the spectrum occupancy in the IEEE 802.16 system can be characterized as temporal fast periodic and with short and potentially stochastic durations. Hence, it might be more challenging for a CR system to utilize white spaces in such primary systems, as compared to a CR system that aims to use white spaces with more static characteristics such as in the TV White Spaces (TVWS). Therefore, we conclude that **cooperation and assistance from the primary operator is important to maximize the secondary system utilization of the available OFDMA capacity**. A complete secondary system could use a combined approach based on statistics about OFDMA occupancy, cooperation with the primary operator and sensing used to detect primary users in real time to reduce interference.

4.1.2 Viability of Sensor Network Aided Cognitive Radio

Second, we studied the concept of a sensor network aided CR (SENDORA) system, where sensors not only embedded in CR terminals, but deployed externally, detect white spaces. In the first work in Paper B, three business case scenarios for deployment of a SENDORA system were proposed and evaluated; "spectrum sharing", "spectrum broker" and "new entrant". It was found that **the spectrum sharing business case, where a joint venture gets the rights to use the "unused" spectrum resources of spectrum owners in a cognitive way, is one of the best possible cases for the SENDORA system**. In this business case, a joint venture operator has free access to vacant frequency resources of the mother companies, detailed knowledge of the primary systems and good possibilities for sharing infrastructure with the operators owning the spectrum. It was further shown that **the most critical aspects to obtain a viable business case are the fixed sensor density, the fixed sensor operational costs and the number of new cognitive base station sites required**. It was shown that the business case gets negative if the fixed sensor density is above 72 sensors/km^2, if the fixed sensor operational costs increases with more than 16%, or if more than 6% new base station sites must be established. A high number of sensors that increase the costs considerably are required dependent on the interference limit used. This will be important to consider by regulators and spectrum owners when deciding on allowed interference probability limits. The high sensitivity for the fixed sensor OPEX showed that it is critical that the fixed sensor power consumption is low and that the mean time between failures is long. The sensitivity of the number of new sites required showed that it is of high importance for the secondary operator to co-locate as many base station sites as possible with primary operators.

The “Spectrum Broker” business case was based around the concept of a an entity that deploys, builds and operates a sensor network and sells either sensing information or information on spectrum opportunities to one or more CR operators. The main output from this business case was to calculate the costs for the spectrum broker as input to the “New Entrant” business case. This business case studied the potential of a new entrant using the SENDORA system without existing infrastructure or frequency licenses that rents spectrum from the spectrum broker. It was found that if the new entrant has to pay the spectrum broker what it needs to cover its expenses, the business case gets strongly negative even when these expenses are shared with three other cognitive operators using information from the spectrum broker. Hence, **the new entrant business case scenario is challenging to make viable**.

Motivated by the finding above, that a high degree of co-location of secondary and primary base station sites is very important in order to achieve a positive business case for a SENDORA system, this was further evaluated in a technical system level simulation study. All parts of the SENDORA system were implemented in a system level simulator including a primary network, a centralized secondary network, a WSN and a centralized fusion center. The WSN detects signal strength from primary users in the spectrum bands and reports these to the fusion center, which determines available channels based on interference limits. To get a detailed picture of performance, realistic network topologies, traffic models and the whole protocol stack of the secondary and primary systems with actual transport, network, link and physical layers were implemented. It was found that **equal cell size for the secondary and primary systems with a cellular reuse pattern with seven frequencies is difficult to achieve**. In this case only 50% of the CR users obtained connectivity. This does not fit together with the results in the business case analysis. It was also found that **a good service with full throughput could be offered with secondary cell size set to half or two thirds of the primary cell size and with restricted transmit power levels**. The number of base stations installed for half the primary cell size will then be quadrupled and at least 75% of these will not be co-located with primary base stations, leading to increased costs. **This points in the direction of shorter range, smaller and less expensive base stations for the secondary system such as WiFi access points and femtocells**.

Aiming to achieve higher co-location of base station sites, a study was conducted on how relaxed requirements for the maximum interference generated by the secondary transmitters can improve secondary system performance and capacity. It was found that **allowing higher interference, max throughput and full coverage can be obtained**. It was also found that this comes at the costs of a decrease in primary system performance with a slight reduction in throughput and an increase in packet loss of 2% per user on average.

We conclude that **this can be considered acceptable for a business model where the primary operator gets economic benefits from improved secondary system performance**.

Motivated by the finding that CR is well suited for smaller and less expensive base stations such as femtocells, a business case was proposed and evaluated where a mobile operator offloads its LTE network by deploying cognitive femtocells using the SENDORA concept in the TVWS spectrum. When aided by a sensor network the cognitive femtocells are able to use frequencies other than the mobile network and hence increase its power to cover outdoor areas and neighbor buildings. The cognitive femtocell strategy was compared with a strategy where the operator deploys conventional femtocells and additional new base stations to support the traffic demand. It was found that **the cognitive femtocell strategy can be more profitable than the conventional femtocell and new base stations strategy. The most critical parameter for the cognitive femtocell strategy is the price for backhauling the cognitive femtocell**. Since little information exists about this price, a more detailed study to estimate this price will be of highest importance. It is found that the costs in the two business cases equals if the price for backhaul increases with 64%. It was also found that **the number of supported users by a cognitive femtocell is a critical parameter which is important to consider when developing cognitive femtocells**. Interestingly, it was found that **parameters related to the senor network such as required density, price and OPEX for the fixed sensors are less critical when sensors are embedded in the cognitive femtocells**. It was also found that the coverage radius for the cognitive femtocell is important and the optimal radiuses were found to be between 40 and 70 m in the urban area and 80 m in the suburbs. Here, even lower ranges caused more cognitive femtocells to be deployed resulting in much higher costs.

4.1.3 Performance of the First Cognitive Radio Standard IEEE 802.22

Performance evaluation of CR standards is extremely important for the mobile operator when deciding to deploy a CR network. Therefore, a highly detailed system level simulation model for a system based on the first CR standard IEEE 802.22 for access in the TVWS was implemented and used to evaluate IEEE 802.22 performance. Assuming that geolocation database access is used to find available channels not used by TV broadcasters, novel spectrum sensing strategies were implemented in the simulator to detect the presence of unregistered wireless microphones as the greatest challenge. First, it was shown that **the activity of wireless microphones, as the primary users in TVWS, should be quite high in order to reduce throughput and increases delay**. Furthermore, it was shown that **interference to wireless microphones is low in general and**

occurs only for short intervals when the wireless microphone appears with the considered sensing strategies. Though, it was shown that **delay increases as the wireless microphone activity level increases**.

Providing QoS to its customers is also important for mobile operators to achieve high customer satisfaction. Therefore, QoS profiles in the IEEE 802.22 standard were implemented and evaluated in the simulator. It was shown that **the guaranteed bit rate QoS service for VoIP can be prioritized in IEEE 802.22, though the spectrum sensing strategy used is important to satisfy strict QoS requirements**. It was also shown that **delay increases duo to the overhead caused by the sensing strategy used**, and that **VoIP traffic can be prioritized to achieve lowest possible delay for the specific sensing strategy irrespective of the best effort traffic load**. A tradeoff for the selection of sensing strategy was found between achieving high capacity in the IEEE 802.22 network and protecting the wireless microphones at a highest possible level. This should be considered by operators and regulators.

Spectrum sensing is commonly used in CR networks to detect primary users of the spectrum and then cease transmission. However, sensing results can also be used to generate statistical knowledge about the spectrum usage. For example, wireless microphones operating in the TVWS often appear at specific venues such as schools, concert halls or churches and at specific times such as in the mornings, evenings or on Sundays. Hence, their location and appearance pattern can be predicted from spectrum sensing statistics. Therefore, three spectrum selection functions that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection were implemented and evaluated in the IEEE 802.22 simulation model. It was found that **the spectrum selection function that uses statistics about channel idle and busy periods performs best when primary user activity is high**. For example, in a case with high wireless microphone activity with average on time varying around 5 seconds and inter-arrival time varying around 10 seconds, it was shown that this spectrum selection function gave 11.5% higher throughput on average compared to not using such statistics. It was also found that **the spectrum selection function that uses predictions about location and distance to primary users gives highest performance when CR users are mobile and the primary user activity is low**. A maximum throughput gain of 4.7% was obtained for this function for a wireless microphone activity with on time varying around 5 seconds and inter-arrival time varying around 40 seconds. It was also found that, **using the spectrum selection functions, harmful interference was reduced for both the IEEE 802.22 network and the wireless microphone, which resulted in a more stable network with higher system throughput**.

4.2 Limitations of the Research

The simulation models implemented and used in this thesis are highly detailed, including all layers in the TCP/IP stack and the possibility to implement various traffic models. This is considered important since we are able to evaluate the performance on different layers in the protocol stack, which gives a complete and realistic evaluation of the performance of the considered systems. However, the use of such detailed simulation models results in long simulation times. Furthermore, since a high number of simulations is required to get results of high accuracy, the time required to study one scenario of interest becomes extremely long. As an effect, there is a tradeoff between the number of different scenarios that can be studied and the level of accuracy of the results. We have done our best to balance this tradeoff with due care.

Dynamic transmit power might increase utilization of white spaces and has the potential to reduce interference to the primary system. This was not implemented in the system level simulation models. Hence, this has probably lowered the potential channel availability for the CR network in the technical evaluations, especially in papers C and D. Another limitation in the system level simulation models is that we were not able to implement directional antennas, which would have resulted in lower interference and a better link budget. Finally, the spectrum sensing algorithm at the physical layer was limited to energy detection. This was not considered a severe limitation since the main focus with respect to sensing was on sensing schemes at the MAC layer.

One of the most challenging tasks in the business case studies is to determine the input assumptions. Examples of such assumptions are costs, revenues and technology specifications. Since the technologies considered in the business case studies do not exist in the market and since the business cases were calculated for many years into the future, the assumptions made were uncertain. The impacts of these uncertainties were however studied through sensitivity analysis.

There are a range of different scenarios that could be considered attractive for the mobile operator. An attempt has been made to select the most promising ones. The selected scenarios have been subject to evaluation and iterative refinement through technical and economic evaluations. Less promising scenarios for a mobile operator have also been omitted during evaluations. However, in this thesis, the number of studied scenarios were limited both in the technical and economical evaluations.

4.3 Suggestions for Further Research

The spectrum availability and performance gains for CR access in the temporal domain in a primary OFDMA network was characterized in Paper A. Further work remains to model the primary system with a more realistic mixed traffic scenario and perform real life experiments or measurements to derive improved models for primary OFDMA occupancy. Second, an important study would be to study the use of co-operation between the secondary and primary operators considering protocols, performance and economic models to achieve full spectrum utilization. This could involve spectrum sensing, database and spectrum broker functionalities.

For the performance evaluations of achievable cell size in the SENDORA system aiming to achieve as high degree of base station co-location as possible (papers B-D), there are especially two further topics that should be addressed. Both the technical performance and the economic viability should be evaluated. First, it will be important to study alternative deployment scenarios such as cell sectorization and real deployments with non-hexagonal cells. Second, the implementation of adaptive dynamic transmit power for the secondary system could increase performance.

It was shown in Paper B that a high number of sensors, which increases the costs considerably, were required dependent on the interference limit. Hence, acceptable interference limits that could allow for lower sensor density should be studied further considering CR techniques, economic models and regulation policies. Also, the fixed sensor OPEX was a critical cost factor to obtain a viable business case, hence further studies should focus on lowering the sensor power consumption and on building robust and reliable sensors such that the operator reduces the work for sensor maintenance. This also motivates the extensive current work on enhancing sensor performance in the research community.

For the business case where a mobile operator offloads its LTE network by deploying cognitive femtocells (Paper E), the most critical parameter was the price for backhauling the cognitive femtocell. Further research on pricing and on strategies on how to backhaul cognitive femtocells will be extremely important for the success of such business cases.

The effects of potential disruption when using CR technologies was not included in the business case studies, since the disruptive effect is difficult to predict and quantify. Examples of potential disruptive innovations for CR were given when considering the disruptive innovation theory in Section 2.5.4. A further study is to use the framework proposed by Christensen [51, 140, 141] in a structured way to further identify and evaluate potentially disruptive business models for CR. Another further work is to model and analyze business cases for CR considering disruptive innovation effects, which also will include the modeling of competitors' performance.

The performance of the IEEE 802.22 standard was analyzed in papers F-I by implementing a comprehensive system level simulation model. As this thesis is being submitted, news releases appear about the first equipment based on this standard. Further work is therefore to implement and evaluate the sensing strategies and spectrum selection functions proposed in this thesis in a field trial.

The work to release the source code of the IEEE 802.22 NS-2 simulation model to the public domain is in process. A further work using this simulation model will be to implement further novel spectrum selection functions and to enhance the model by addressing the limitations described above. In the future, there will probably be more than one CR system existing in a specific area. Systems based on different CR standards, such as IEEE 802.22 and IEEE 802.11af, will also co-exist. The studies in this thesis were limited to a single CR system operating in one area. A further work is therefore to study inter-network spectrum sharing with standards such as IEEE 802.22 and other standards. This could be done by extending our simulation model for IEEE 802.22 or by using other simulation models.

Bibliography

[1] M. A. McHenry, D. McCloskey, and G. Lane-Roberts, "Spectrum occupancy measurements location 4 of 6: Republican national convention, new york city, new york, august 30, 2004 - september 3, 2004," Tech. Rep. Revision 2, Aug. 2005.

[2] R. Tandra, A. Sahai, and S. Mishra, "What is a spectrum hole and what does it take to recognize one?" *Proceedings of the IEEE*, vol. 97, no. 5, pp. 824–848, May 2009.

[3] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[4] J. Peha, "Approaches to spectrum sharing," *IEEE Communications Magazine*, vol. 43, no. 2, pp. 10–12, Feb. 2005.

[5] J. Mitola, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," PhD Dissertation, Royal Institute of Technology (KTH), Kista, Sweden, May 2000. [Online]. Available: http://web.it.kth.se/~maguire/jmitola/Mitola_Dissertation8_Integrated.pdf

[6] D. Cabric, S. Mishra, and R. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers*, vol. 1, Nov. 2004.

[7] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl, "Senseless: A database-driven white spaces network," *IEEE Transactions on Mobile Computing*, vol. 11, no. 2, pp. 189–203, Feb. 2012.

[8] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 79–89, May 2007.

[9] J. Chapin and W. Lehr, "Cognitive radios for dynamic spectrum access - the path to market success for dynamic spectrum access technology," *IEEE Communications Magazine*, vol. 45, no. 5, pp. 96–103, May 2007.

[10] B. Wang and K. Liu, "Advances in cognitive radio networks: A survey," *IEEE Journal of Selected Topics in Signal Processing*, vol. 5, no. 1, pp. 5–23, Feb. 2011.

[11] S. Filin, H. Harada, H. Murakami, and K. Ishizu, "International standardization of cognitive radio systems," *IEEE Communications Magazine*, vol. 49, no. 3, pp. 82–89, Mar. 2011.

[12] G. Baldini, O. Holland, V. Stavroulaki, K. Tsagkaris, P. Demestichas, A. Polydoros, S. Karanasios, and D. Allen, "The evolution of cognitive radio technology in europe: Regulatory and standardization aspects," *Telecommunications Policy*, vol. 37, no. 2-3, pp. 96–107, Mar. 2013.

[13] M. Nekovee, T. Irnich, and J. Karlsson, "Worldwide trends in regulation of secondary access to white spaces using cognitive radio," *IEEE Communications Magazine*, vol. 19, no. 4, pp. 32–40, Aug. 2012.

[14] FCC, "Second memorandum opinion and order," Tech. Rep. ET Docket No. 10-174, Sep. 23, 2010.

[15] Ofcom, "Digital dividend: Cognitive access, statement on licence-exempting cognitive devices using interleaved spectrum," Tech. Rep., Jul. 2009.

[16] "Technical and operational requirements for the possible operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz," European Communication Committee, Tech. Rep. ECC Report 159, Jan. 2011.

[17] FCC, "Notice of proposed rulemakings," Tech. Rep. ET Docket No. 12-148, Dec. 2012.

[18] P. Pawelczak, "Opportunistic spectrum access: Designing link and transport layer," Dissertation, TU Delft University of Technology, Apr. 2009.

[19] J. M. Peha and S. Panichpapiboon, "Real-time secondary markets for spectrum," *Telecommunications Policy*, vol. 28, no. 7 - 8, pp. 603–618, Aug. 2004.

[20] J. Chapin and W. Lehr, "Time-limited leases in radio systems," *IEEE Communications Magazine*, vol. 45, no. 6, pp. 76–82, Jun. 2007.

[21] C. Caicedo and M. Weiss, "The viability of spectrum trading markets," *IEEE Communications Magazine*, vol. 49, no. 3, pp. 46–52, Mar. 2011.

[22] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40–48, Apr. 2008.

[23] S. Geirhofer, L. Tong, and B. Sadler, "Cognitive radios for dynamic spectrum access - dynamic spectrum access in the time domain: Modeling and exploiting white space," *IEEE Communications Magazine*, vol. 45, no. 5, pp. 66–72, May 2007.

[24] B. Mercier et al., "Sensor networks for cognitive radio: Theory and system design," in *Proc. ICT Mobile Summit*, Stockholm, Sweden, Jun. 10–12, 2009.

[25] "Sendora project." [Online]. Available: http://www.sendora.eu/

[26] M. B. Weiss, M. Al-Tamaimi, and L. Cui, "Dynamic geospatial spectrum modelling: Taxonomy, options and consequences," in *Proc. Telecommunications Policy Research Conference*, Oct. 2010.

[27] M. Lopez-Benitez, A. Umbert, and F. Casadevall, "Evaluation of spectrum occupancy in spain for cognitive radio applications," in *Proc. IEEE VTC Spring*, Apr. 26–29, 2009.

[28] K. E. Nolan, E. Ambrose, L. E. Doyle, and D. O'Mahony, "Cognitive radio: value creation and value migration," in *Proc. Software-Defined Radio Technical Conference and Product Exposition (SDR Forum)*, Nov. 13–17, 2006.

[29] N. Kelkar, Y. Yang, D. Shome, and G. Morgan, "A business model framework for dynamic spectrum access in cognitive networks," in *Proc. IEEE GLOBECOM*, Nov. 30 – Dec. 4, 2008.

[30] J. Chapin and W. Lehr, "Mobile broadband growth, spectrum scarcity, and sustainable competition," in *Telecommunications Policy Research Conference*, Sep. 2011.

[31] M. B. Weiss, M. Altamimi, and L. Cui, "Spatio-temporal spectrum modeling: Taxonomy and economic evaluation of context acquisition," *Telecommunications Policy*, vol. 36, no. 4, pp. 335–348, May 2012.

[32] M. Sherman, A. Mody, R. Martinez, C. Rodriguez, and R. Reddy, "IEEE standards supporting cognitive radio and networks, dynamic spectrum access, and coexistence," *IEEE Communications Magazine*, vol. 46, no. 7, pp. 72–79, Jul. 2008.

[33] M. Mueck, A. Piipponen, K. Kalliojärvi, G. Dimitrakopoulos, K. Tsagkaris, P. Demestichas, F. Casadevall, J. Perez-Romero, O. Sallent, G. Baldini, S. Filin, H. Harada, M. Debbah, T. Haustein, J. Gebert, B. Deschamps, P. Bender, M. Street, S. Kandeepan, J. Lota, and A. Hayar, "ETSI reconfigurable radio systems: status and future directions on software defined radio and cognitive radio standards," *IEEE Communications Magazine*, vol. 48, no. 9, pp. 78–86, Sep. 2010.

[34] F. Granelli, P. Pawelczak, R. Prasad, K. Subbalakshmi, R. Chandramouli, J. Hoffmeyer, and H. Berger, "Standardization and research in cognitive and dynamic spectrum access networks: IEEE SCC41 efforts and other activities," *IEEE Communications Magazine*, vol. 48, no. 1, pp. 71–79, Jan. 2010.

[35] T. Maeda, A. Amar, and A. Gibson, "Impact of wireless telecommunications standards and regulation on the evolution of wireless technologies and services over internet protocol," *Telecommunications Policy*, vol. 30, no. 10-11, pp. 587–604, Dec. 2006.

[36] *IEEE Standard for Information Technology–Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)–Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands*, IEEE IEEE Std 802.22-2011, 2011.

[37] A. E. Leu, B. L. Mark, and M. A. McHenry, "A framework for cognitive WiMAX frequency agility," *Proceedings of the IEEE*, vol. 97, no. 4, pp. 755–773, Apr. 2009.

[38] H.-S. Chen, W. Gao, and D. G. Daut, "Spectrum sensing using cyclostationary properties and application to IEEE 802.22 WRAN," in *Proc. IEEE GLOBECOM*, Washington, DC, USA, Nov. 26–30, 2007.

[39] J. Park, T. Song, J. Hur, S. M. Lee, J. Choi, K. Kim, K. Lim, C.-H. Lee, H. Kim, and J. Laskar, "A fully integrated UHF-band CMOS receiver with multi-resolution spectrum sensing (MRSS) functionality for IEEE 802.22 cognitive radio applications," *IEEE Journal of Solid-State Circuits*, vol. 44, no. 1, pp. 258–268, Jan. 2009.

[40] H. Kim, J. Kim, S. Yang, M. Hong, and Y. Shin, "An effective MIMO-OFDM system for IEEE 802.22 WRAN channels," *IEEE Transactions on Circuits and Systems—Part II: Analog and Digital Signal Processing*, vol. 55, no. 8, pp. 821–825, Aug. 2008.

[41] D. Niyato, E. Hossain, and Z. Han, "Dynamic spectrum access in IEEE 802.22-based cognitive wireless networks: A game theoretic model for competitive spectrum bidding and pricing," *IEEE Wireless Communications Magazine*, vol. 16, no. 2, pp. 16–23, Apr. 2009.

[42] Y.-C. Liang, A. T. Hoang, and H.-H. Chen, "Cognitive radio on tv bands: a new approach to provide wireless connectivity for rural areas," *IEEE Wireless Communications*, vol. 15, no. 3, pp. 16–22, Jun. 2008.

[43] S. Segupta, M. Chatterje, and R. Chandramouli, "A coordinated distributed scheme for cognitive radio based IEEE 802.22 wireless mesh networks," in *Proc. IEEE CogNet (IEEE ICC 2008 Workshop)*, Beijing, China, May 19–23, 2008.

[44] H. Kim and K. Shin, "Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 5, pp. 533 –545, May 2008.

[45] ——, "In-band spectrum sensing in IEEE 802.22 WRANs for incumbent protection," *IEEE Transactions on Mobile Computing*, vol. 9, no. 12, pp. 1766–1779, Dec. 2010.

[46] L. Song, C. Feng, Z. Zeng, and X. Zhang, "Research on WRAN system level simulation platform design," in *Proc. ICST Chinacom*, Hangzhou, China, Aug. 25–27, 2008.

[47] S. Maharjan, J. Xiang, Y. Zhang, and S. Gjessing, "Delay reduction for real time services in IEEE 802.22 wireless regional area network," in *Proc. IEEE PIMRC*, Sep. 26–29, 2010.

[48] C. Cordeiro, K. Challapali, and M. Ghosh, "Cognitive PHY and MAC layers for dynamic spectrum access and sharing of TV bands," in *Proc. ACM Workshop TAPAS*, New York, NY, USA, Aug. 5, 2006.

[49] C. Cordeiro, M. Ghosh, D. Cavalcanti, and K. Challapali, "Spectrum sensing for dynamic spectrum access of TV bands," in *Proc. ICST/IEEE CROWNCOM*, Aug. 1–3, 2007.

[50] K. Challapali, C. Cordeiro, and D. Birru, "Evolution of spectrum-agile cognitive radios: first wireless internet standard and beyond," in *Proc. ACM Workshop on Wireless Internet (WICON'06)*, New York, NY, USA, Aug. 2–5, 2006.

[51] C. M. Christensen and M. E. Raynor, *The innovator's solution: Creating and sustaining successful growth.* Harvard Business Press, 2003.

[52] *Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1*, IEEE Std. 802.16e, Apr. 2006.

[53] D. Astely, E. Dahlman, A. Furuskar, A. Kangas, M. Lindstrom, and S. Parkvall, "LTE: the evolution of mobile broadband," *IEEE Communications Magazine*, vol. 47, no. 4, pp. 44–51, Apr. 2009.

[54] M. Barrie, S. Delaere, P. Anker, and P. Ballon, "Aligning technology, business and regulatory scenarios for cognitive radio," *Telecommunications Policy*, vol. 36, no. 7, pp. 546–559, Mar. 2012.

[55] M. Weiss and W. Lehr, "Market based approaches for dynamic spectrum assignment," *Available at SSRN 2027059*, Dec. 2009.

[56] O. Grøndalen et al., "Scenario descriptions and system requirements," EU FP7 SENDORA Report, Jan. 2010.

[57] D. Noguet, R. Datta, P. Lehne, M. Gautier, and G. Fettweis, “TVWS regulation and QoSMOS requirements,” in *Proc. Wireless VITAE*, Feb. 28 – Mar. 3, 2011.

[58] R. Mackenzie, P. Lehne, U. Celentano, and M. Ariyoshi, “Identifying scenarios with high potential for future cognitive radio networks,” in *Future Network and Mobile Summit (FutureNetw)*, Jun. 15–17, 2011.

[59] G. Dodig-Crnkovic, “Scientific research in computer science,” in *Proc. Conference for the Promotion of Research in IT at New Universities and at University Colleges in Sweden*, Apr. 2002.

[60] R. K. Jain, *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling*, 1st ed. Wiley, 1991.

[61] P. R. Grønsund, “A field study of WiMAX performance,” Master’s thesis, University of Oslo, 2008.

[62] A. Penttinen, “Chapter 9 - simulation,” Lecture Notes: S-38.145 - Introduction to Teletraffic Theory, 1999.

[63] M. H. MacDougall, *Simulating computer systems: techniques and tools.* Cambridge, MA, USA: MIT Press, 1987.

[64] “The network simulator ns-2.” [Online]. Available: http://www.isi.edu/nsnam/ns/

[65] N. Golmie et. al. (2009) WiMAX forum system level simulator NS-2 MAC+PHY add-on for WiMAX (IEEE 802.16). [Online]. Available: http://code.google.com/p/ns2-wimax-awg/

[66] S. Benninga and B. Czaczkes, *Financial Modeling 2nd edn.* MIT Press, 2000.

[67] “The ERA conference exercise,” October 2010. [Online]. Available: http://core.edu.au/

[68] J. Mitola and G. Maguire Jr., “Cognitive radio: making software radios more personal,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[69] M. Buddhikot, “Understanding dynamic spectrum access: Models,taxonomy and challenges,” in *Proc. IEEE DySPAN*, Apr. 17–20, 2007.

[70] J. Peha, “Sharing spectrum through spectrum policy reform and cognitive radio,” *Proceedings of the IEEE*, vol. 97, no. 4, pp. 708–719, 2009.

[71] D. Hatfield and P. Weiser, “Property rights in spectrum: taking the next step,” in *Proc. IEEE DySPAN*, Nov. 8–11, 2005.

[72] P. Leaves, K. Moessner, R. Tafazolli, D. Grandblaise, D. Bourse, R. Tonjes, and M. Breveglieri, "Dynamic spectrum allocation in composite reconfigurable wireless networks," *IEEE Communications Magazine*, vol. 42, no. 5, pp. 72–81, May 2004.

[73] K. Siwiak, "Ultra-wide band radio: introducing a new technology," in *Proc. IEEE VTC Spring*, vol. 2, May 16–19, 2001.

[74] R. Thomas, L. DaSilva, and A. MacKenzie, "Cognitive networks," in *Proc. IEEE DySPAN*, Nov. 8–11, 2005.

[75] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks*, vol. 50, no. 13, pp. 2127–2159, Sep. 2006.

[76] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury, "CRAHNs: Cognitive radio ad hoc networks," *Ad Hoc Networks*, vol. 7, no. 5, pp. 810–836, Jul. 2009.

[77] S. Delaere and P. Ballon, "Multi-level standardization and business models for cognitive radio: The case of the cognitive pilot channel," in *Proc. IEEE DySPAN*, Oct. 14–17, 2008.

[78] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys Tutorials*, vol. 11, no. 1, pp. 116–130, First Quarter 2009.

[79] R. Tandra and A. Sahai, "SNR walls for signal detection," *IEEE Journal of Selected Topics in Signal Processing*, vol. 2, no. 1, pp. 4–17, Feb. 2008.

[80] D. Cabric, A. Tkachenko, and R. Brodersen, "Spectrum sensing measurements of pilot, energy, and collaborative detection," in *Proc. IEEE MILCOM*, Oct. 23–25, 2006.

[81] A. Ghasemi and E. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *Proc. IEEE DySPAN*, Nov. 8–11, 2005.

[82] ——, "Opportunistic spectrum access in fading channels through collaborative sensing," *Journal of Communications*, vol. 2, no. 2, pp. 71–82, Mar. 2007.

[83] W. Saad, Z. Han, M. Debbah, A. Hjorungnes, and T. Basar, "Coalitional games for distributed collaborative spectrum sensing in cognitive radio networks," in *Proc. IEEE INFOCOM*, Apr. 19–25, 2009.

[84] M. Wellens, J. Riihijarvi, and P. Mahonen, "Evaluation of adaptive MAC-layer sensing in realistic spectrum occupancy scenarios," in *Proc. IEEE DySPAN*, Apr. 6–9, 2010.

[85] W. S. Jeon, D. G. Jeong, J. A. Han, G. Ko, and M. S. Song, "An efficient quiet period management scheme for cognitive radio systems," *IEEE Transactions on Wireless Communications*, vol. 7, no. 2, pp. 505–509, Feb. 2008.

[86] S. Sesia, I. Toufik, and M. Baker, *LTE: the UMTS long term evolution.* Wiley Online Library, 2009.

[87] K. Arshad and K. Moessner, "Statistical models of spectrum opportunities for cognitive radio," in *Proc. IEEE PIMRC*, Sep. 11–14, 2011.

[88] Y. Zhao, D. Raymond, C. da Silva, J. Reed, and S. Midkiff, "Performance evaluation of radio environment map-enabled cognitive spectrum-sharing networks," in *Proc. IEEE MILCOM*, Oct. 29–31, 2007, pp. 1–7.

[89] Y. Zhao, L. Morales, J. Gaeddert, K. Bae, J.-S. Um, and J. Reed, "Applying radio environment maps to cognitive wireless regional area networks," in *Proc. IEEE DySPAN 2007*, Apr. 17–20, 2007.

[90] M. Wellens, J. Riihijärvi, and P. Mähönen, "Spatial statistics and models of spectrum use," *Computer Communications*, vol. 32, no. 18, pp. 1998–2011, Dec. 2009.

[91] Y. Song, Y. Fang, and Y. Zhang, "Stochastic channel selection in cognitive radio networks," in *Proc. IEEE GLOBECOM*, Nov. 26–30, 2007.

[92] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum," in *Proc. IEEE WoWMoM*, Jun. 13–16, 2005.

[93] V. Brik, E. Rozner, S. Banerjee, and P. Bahl, "DSAP: a protocol for coordinated spectrum access," in *Proc. IEEE DySPAN*, Nov. 8–11, 2005.

[94] J. Mwangoka, P. Marques, and J. Rodriguez, "Broker based secondary spectrum trading," in *Proc. ICST/IEEE CROWNCOM*, Jun. 2011.

[95] P. Grønsund, R. Mackenzie, P. Lehne, K. Briggs, O. Grøndalen, P. Engelstad, and T. Tjelta, "Towards spectrum micro-trading," in *Proc. Future Network Mobile Summit (FutureNetw)*, Jul. 4–6, 2012.

[96] N. Abji and A. Leon-Garcia, "Spectrum markets for service provider spectrum trading with reinforcement learning," in *Proc. IEEE PIMRC*, Sep. 11–14, 2011.

[97] H. Xu, J. Jin, and B. Li, "A secondary market for spectrum," in *Proc. IEEE INFOCOM*, Mar. 15–19, 2010.

[98] M. Gastpar, "On capacity under received-signal constraints," in *Proc. Allerton Conference on Communication, Control and Computing*, Sep. 29–Oct. 1, 2004.

[99] A. Ghasemi and E. S. Sousa, "Fundamental limits of spectrum-sharing in fading environments," *IEEE Transactions on Wireless Communications*, vol. 6, no. 2, pp. 649–658, Feb. 2007.

[100] A. Ghasemi and E. Sousa, "Capacity of fading channels under spectrum-sharing constraints," in *Proc. IEEE ICC*, Jun. 11–15, 2006.

[101] C.-X. Wang, X. Hong, H.-H. Chen, and J. Thompson, "On capacity of cognitive radio networks with average interference power constraints," *IEEE Transactions on Wireless Communications*, vol. 8, no. 4, pp. 1620–1625, Apr. 2009.

[102] J. Park, P. Pawelczak, and D. Cabric, "To buffer or to switch: Design of multichannel MAC for OSA ad hoc networks," in *Proc. IEEE DySPAN*, Apr. 6–9, 2010.

[103] FCC, "ET Docket No. 10-237," Notice of Inquery, Nov. 30 2010.

[104] V. Fodor, I. Glaropoulos, and L. Pescosolido, "Detecting low-power primary signals via distributed sensing to support opportunistic spectrum access," in *Proc. IEEE ICC*, Jun. 14–18, 2009.

[105] L. Pescosolido and C. Petrioli, "Wireless sensor networks for spectrum sensing to support opportunistic spectrum access networks: Protocol design and fundamental trade-offs," in *Proc. IEEE WCNC*, Mar. 28–31, 2011.

[106] K. Harrison, S. Mishra, and A. Sahai, "How much white-space capacity is there?" in *Proc. IEEE DySPAN*, Apr. 6–9, 2010.

[107] J. van de Beek, J. Riihijarvi, A. Achtzehn, and P. Mahonen, "UHF white space in europe - a quantitative study into the potential of the 470 - 790 mhz band," in *Proc. IEEE DySPAN*, May 3–6, 2011.

[108] FCC, "Second report and order and memorandum opinion and order," Tech. Rep. ET Docket No. 08-260, Nov. 2008.

[109] *Draft Standard for Information Technology; Telecommunications and information exchange between systems; Local and metropolitan area networks; Specific Requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications; Amendment 5: TV White Spaces Operation*, IEEE Std. P802.11af Draft 2.0, 2013.

[110] J. Wang, M. S. Song, S. Santhiveeran, K. Lim, G. Ko, K. Kim, S. H. Hwang, M. Ghosh, V. Gaddam, and K. Challapali, "First cognitive radio networking standard for personal/portable devices in TV white spaces," in *Proc. IEEE DySPAN*, Apr. 6–9, 2010.

[111] Protocol to Access White Space database (PAWS), "https://www.ietf.org/mailman/listinfo/paws," url, Dec. 2011.

[112] M. Mueck and D. Noguet, "TV white space standardization and regulation in europe," in *Proc. Wireless VITAE*, Mar. 1–3, 2011.

[113] ETSI TC RRS, "TS 102 946 system requirements for operation in UHF TV band white spaces," Tech. Rep., Oct. 2011.

[114] R. Prasad, P. Pawelczak, J. Hoffmeyer, and H. Berger, "Cognitive functionality in next generation wireless networks: standardization efforts," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 72–78, Apr. 2008.

[115] C. Cordeiro, K. Challapali, D. Birru, and N. Sai Shankar, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios," in *Proc. IEEE DySPAN*, Nov. 8–11, 2005.

[116] C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, and W. Caldwell, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 130–138, Jan. 2009.

[117] *IEEE Draft Standard for Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements Part 22.1: Standard to Enhance Harmful Interference Protection for Low Power Licensed Devices Operating in TV Broadcast Bands*, IEEE Std. 802.22.1, Nov. 2010.

[118] S. J. Shellhammer, "Spectrum sensing in 802.22," *IAPR Workshop Cognitive Info. Processing*, Jun. 9–10, 2008.

[119] FCC, "Notice of proposed rulemakings," Tech. Rep. ET Docket No. 13-22, Feb. 20, 2013.

[120] K. W. Sung, E. Obregon, and J. Zander, "On the requirements of secondary access to 960-1215 mhz aeronautical spectrum," in *Proc. IEEE DySPAN*, May 3–6, 2011.

[121] H. Tang, "Some physical layer issues of wide-band cognitive radio systems," in *Proc. IEEE DySPAN*, Nov. 8–11, 2005.

[122] FCC, "Order and authorization," Tech. Rep. ET Docket No. 11-133, Jan. 26, 2011.

[123] Radio Spectrum Policy Group, "Report on collective use of spectrum (CUS) and other spectrum sharing approaches," RSPG11-392, Nov. 2011.

[124] P. L. Parcu, A. Nicita, G. Corda, M. A. Rossi, and L. F. Bravo, "Authorised shared access (ASA): An innovative model of pro-competitive spectrum management," May 2011. [Online]. Available: http://ssrn.com/abstract=2174518

[125] CEPT WG FM #73, "Report on ASA concept," Tech. Rep., Nov. 2011.

[126] Ofcom, "Notice of proposals to make 900 mhz, 1800 mhz and 2100 mhz public wireless network licences tradable," Tech. Rep., Feb. 2011.

[127] P. Grønsund, R. MacKenzie, P. Lehne, and K. Briggs, "Spectrum micro-trading analysis," EU FP7 QoSMOS Report, Tech. Rep., Jun. 2012.

[128] A. Osterwalder, "The business model ontology: a proposition in a design science approach," *Institut d'Informatique et Organisation. Lausanne, Switzerland, University of Lausanne, Ecole des Hautes Etudes Commerciales HEC*, vol. 173, 2004.

[129] H. Chesbrough and R. S. Rosenbloom, "The role of the business model in capturing value from innovation: evidence from xerox corporation's technology spin-off companies," *Industrial and corporate change*, vol. 11, no. 3, pp. 529–555, 2002.

[130] P. Ballon, "Business modelling revisited: the configuration of control and value," *info*, vol. 9, no. 5, pp. 6–19, 2007.

[131] J. Markendahl and T. Casey, "Business opportunities using white space spectrum and cognitive radio for mobile broadband services," in *Proc. ICST/IEEE CROWNCOM*, Jun. 18–20, 2012.

[132] J. Markendahl, P. Gonzalez-Sanchez, and B. Molleryd, "Impact of deployment costs and spectrum prices on the business viability of mobile broadband using TV white space," in *Proc. ICST/IEEE CROWNCOM*, Jun. 18–20, 2012.

[133] O. Grøndalen, M. Lähteenoja, P. H. Lehne, and R. Mackenzie, "Economic evaluation of a cognitive radio based solution for increasing capacity of LTE networks," in *Submitted to Future Network Mobile Summit (FutureNetw)*, Jul. 2013.

[134] Gomes, A et. al., "Secondary spectrum market emulation tool and market dynamic studies," EU FP7 CoGEU Report, Tech. Rep., Jan. 2012.

[135] R. MacKenzie, O. Grøndalen, and P. H. Lehne, "Econonomic evaluation of rural broadband and machine-to-machine deployments in TV whitespaces," in *Proc. IEEE European Wireless*, Guilford, Surrey, UK, Apr. 16–18, 2013.

[136] T. Weiss and F. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Communications Magazine*, vol. 42, no. 3, pp. S8–14, Mar. 2004.

[137] B. Sayrac, H. Uryga, W. Bocquet, P. Cordier, and S. Grimoud, "Cognitive radio systems specific for imt systems: Operator's view and perspectives," *Telecommunications Policy*, vol. 37, no. 2-3, pp. 154–166, Mar. 2013.

[138] M. Barrie, S. Delaere, and P. Ballon, "Classification of business scenarios for spectrum sensing," in *Proc. IEEE PIMRC*, Sep. 26–29, 2010.

[139] A. Medeisis and S. Delaere, "High-level scenarios for the future of cognitive radio business," in *Proc. IEEE PIMRC*, Sep. 11–14, 2011.

[140] C. M. Christensen, *The innovator's dilemma: when new technologies cause great firms to fail.* Harvard Business Press, 1997.

[141] C. M. Christensen, S. D. Anthony, and E. A. Roth, *Seeing what's next: using the theories of innovation to predict industry change.* Harvard Business Press, 2004.

[142] D. Yu and C. C. Hang, "A reflective review of disruptive innovation theory," *International Journal of Management Reviews*, vol. 12, no. 4, pp. 435–452, 2010.

[143] "Qosmos project." [Online]. Available: http://www.ict-qosmos.eu/

[144] M. B. Weiss and L. Cui, "Tradeable spectrum interference rights," in *Proc. Telecommunications Policy Research Conference*, Sep. 23–25, 2011.

[145] M. Weiss, S. Delaere, and W. Lehr, "Sensing as a service: An exploration into practical implementations of DSA," in *Proc. IEEE DySPAN*, Apr. 6–9, 2010.

[146] M. Fiedler, T. Hossfeld, and P. Tran-Gia, "A generic quantitative relationship between quality of experience and quality of service," *IEEE Network*, vol. 24, no. 2, pp. 36–41, Mar.–Apr. 2010.

[147] R. MacKenzie, P. Lehne, U. Celentano, M. Ariyoshi, B. Cendón, and A. Medela, "Qosmos consolidated scenarios," EU FP7 QoSMOS Report, Tech. Rep., Dec. 2010.

[148] M. Fitch, M. Nekovee, S. Kawade, K. Briggs, and R. Mackenzie, "Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience," *IEEE Communications Magazine*, vol. 49, no. 3, pp. 64–73, Mar. 2011.

[149] M. B. Weiss and M. Altamaimi, "The cost of knowing: An economic evaluation of context acquisition in dsa systems," in *Proc. Telecommunications Policy Research Conference*, Sep. 23–25, 2011.

[150] E. Axell, E. G. Larsson, and D. Danev, "Capacity considerations for uncoordinated communication in geographical spectrum holes," *Physical Communication*, vol. 2, no. 1-2, pp. 3–9, 2009.

[151] E. Larsson and M. Skoglund, "Cognitive radio in a frequency-planned environment: some basic limits," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 4800–4806, Dec. 2008.

[152] S. Kawade and M. Nekovee, "Broadband wireless delivery using an inside-out tv white space network architecture," in *Proc. IEEE GLOBECOM*, Dec. 5–9, 2011.

[153] J. Xiang, Y. Zhang, T. Skeie, and L. Xie, "Downlink spectrum sharing for cognitive radio femtocell networks," *IEEE Systems Journal*, vol. 4, no. 4, pp. 524–534, Dec. 2010.

[154] G. Gür, S. Bayhan, and F. Alagöz, "Cognitive femtocell networks: an overlay architecture for localized dynamic spectrum access," *IEEE Wireless Communications*, vol. 17, no. 4, pp. 62–70, Aug. 2010.

[155] H. Claussen, L. T. W. Ho, and L. G. Samuel, "An overview of the femtocell concept," *Bell Labs Technical Journal*, vol. 13, no. 1, pp. 221–245, Mar. 2008.

[156] Signals Research Group, "Femto forum business case white paper," White Paper, Apr. 2009.

[157] M. Ghosh, V. Gaddam, G. Turkenich, and K. Challapali, "Spectrum sensing prototype for sensing ATSC and wireless microphone signals," in *Proc. ICST/IEEE CROWNCOM*, 2008.

[158] R. Dhillon and T. Brown, in *Proc. IEEE DySPAN*, Oct. 14–17, 2008.

[159] T. Erpek, M. McHenry, and A. Stirling, "Dynamic spectrum access operational parameters with wireless microphones," *IEEE Communications Magazine*, vol. 49, no. 3, pp. 38–45, Mar. 2011.

[160] S.-E. Elayoubi and B. Fouresité, "Performance evaluation of admission control and adaptive modulation in OFDMA WiMax systems," *IEEE/ACM Transactions on Networking*, vol. 16, no. 5, pp. 1200–1211, Oct. 2008.

[161] T. Luo, W. Xiang, and H.-H. Chen, "A subcarrier allocation scheme for cognitive radio systems based on multi-carrier modulation," *IEEE Transactions on Wireless Communications*, vol. 7, no. 9, pp. 3335–3340, Sep. 2008.

[162] Y. Xing, R. Chandramouli, S. Mangold, and S. Shankar N, "Dynamic spectrum access in open spectrum wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 626–637, Mar. 2006.

[163] C.-T. Chou, S. Shankar N, H. Kim, and K. G. Shin, "What and how much to gain by spectrum agility?" *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 576–588, Apr. 2007.

[164] J. Park, P. Pawełczak, and D. Čabrić, "Performance of joint spectrum sensing and MAC algorithms for multichannel opportunistic spectrum access ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 10, no. 7, pp. 1011–1027, Jul. 2011.

[165] P. A. Kumar Acharya, S. Singh, and H. Zheng, "Reliable open spectrum communications through proactive spectrum access," in *Proc. Workshop TAPAS*, ser. TAPAS '06. New York, NY, USA: ACM, Aug. 5, 2006. [Online]. Available: http://doi.acm.org/10.1145/1234388.1234393

[166] L. Yang, L. Cao, and H. Zheng, "Proactive channel access in dynamic spectrum networks," *Physical Communication*, vol. 1, no. 2, pp. 103–111, Jun. 2008. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1874490708000268

[167] M. Höyhtyä, S. Pollin, and A. Mammela, "Performance improvement with predictive channel selection for cognitive radios," in *Proc. Workshop CogART*, Feb. 14, 2008.

[168] S. Geirhofer, L. Tong, and B. M. Sadler, "Interference-aware OFDMA resource allocation: A predictive approach," *Proc. IEEE MILCOM*, Nov. 16–19, 2008.

[169] Q. Zhao, S. Geirhofer, L. Tong, and B. Sadler, "Opportunistic spectrum access via periodic channel sensing," *IEEE Transactions on Signal Processing*, vol. 56, no. 2, pp. 785–796, Feb. 2008.

[170] C.-H. Jiang and R.-M. Weng, "Cognitive engine with dynamic priority resource allocation for wireless networks," *Wireless Personal Communications*, vol. 63, no. 1, pp. 31–43, Mar. 2012. [Online]. Available: http://dx.doi.org/10.1007/s11277-010-0106-5

Part II

Paper A
Towards Dynamic Spectrum Access in Primary OFDMA Systems

Pål Grønsund, Hai N. Pham and Paal E. Engelstad

Proceedings of the 20th Personal, Indoor and Mobile Radio Communications Symposium 2009 (IEEE PIMRC), Tokyo, Japan, Sep. 13-16, 2009.

Towards Dynamic Spectrum Access in Primary OFDMA Systems

Pål Grønsund[1,2,3], Hai Ngoc Pham[2,3], Paal E. Engelstad[1,2,3]
[1]Telenor R&I, Oslo, Norway
Email:{pal.gronsund,paal.engelstad}@telenor.com
[2]Simula Research Laboratory, Oslo, Norway
Email: {paalrgr,hainp,paalee}@simula.no
[3]Department of Informatics, University of Oslo, Norway
Email: {paalrgr,hainp,paalee}@ifi.uio.no

***Abstract*—OFDMA will be the major transmission technology in the future mobile wireless broadband systems, and is already used in Mobile WiMAX and LTE. In this paper, we use simulations to characterize the spectrum usage of such primary systems. This knowledge is useful for cognitive radio and other technologies for dynamic spectrum access that aim at improving the overall spectrum usage. We calculate the available capacity and analyze the distribution of the spectrum occupancy over time for various network scenarios and traffic models. Based on our analyses, we finally propose directions for improving the dynamic access of spectrum allocated to primary OFDMA systems.**

I. Introduction

The increasing usage and demand of wireless systems has caused a dense allocation of licensed frequency bands. At the same time several measurements have shown that only 15% - 85% of the assigned spectrum is utilized, depending on geographical and temporal variations [1]. Opportunistic spectrum access (OSA), as part of the hierarchical dynamic spectrum access (DSA) paradigm [2], is one of the emerging technologies to remedy the inefficiency of the static spectrum management policy. DSA systems are referred to as secondary systems with secondary users (SUs) operating in unused white spectrum. On the other hand, primary systems with primary users (PUs) operate in statically allocated primary spectrum.

Orthogonal Frequency Division Multiple Access (OFDMA) [3] is the major transmission and access technology for future mobile wireless broadband systems such as Mobile WiMAX (IEEE 802.16e-2005 [4]) and 3GPP Long Term Evolution (LTE). It is therefore of great interest to survey the opportunities for secondary systems to utilize spectrum in primary OFDMA systems. Spectrum pooling as a candidate for DSA in primary OFDM systems has been studied with focus on the frequency domain by Weiss et al. in [5] and [6]. Geirhofer et. al. study DSA in the time domain of primary OFDM systems in [7] and introduce a coexistence framework between an ad-hoc OFDM network and an infrastructure network in [8]. However, OFDMA introduces multiple access mapping onto the OFDM frames which complicates the characterization of spectrum usage and distribution of white spectrum holes. Since capacity is allocated as frequency-time resource elements within a OFDMA frame, it is necessary to study OFDMA spectrum in both the frequency and time domain to characterize the opportunities for DSA systems operation in primary OFDMA systems.

In this paper, we characterize the usage of spectrum in primary OFDMA systems and propose potential directions on how to derive DSA schemes for secondary systems to coexist and operate in the primary OFDMA spectrum. As the first step in characterizing such spectrum usage, we simulate primary OFDMA systems in the well known ns-2 network simulator [9] with a Mobile WiMAX implementation developed by the WiMAX Forum. The OFDMA spectrum occupancy is characterized under different application layer traffic models such as CBR (Constant Bit Rate) traffic over UDP and FTP traffic over TCP. As a consequence, we model the statistics of the spectrum availability of such system as the probability of unused OFDMA resource elements over the period of data traffic between the primary base station and the primary users. For example, we observe that only about 24% of spectrum utilized by the system of one base station and five PUs with CBR traffic over UDP. Hence, there is a potential for secondary systems to operate on the primary OFDMA spectrum by exploiting this statistic model of the available spectrum.

Thus, we next propose a sensing-based DSA and a statistics-based DSA schemes as two potential schemes that we argue can enable the secondary systems to utilize the derived statistic model of available OFDMA spectrum. The former scheme can improve spectrum utilization in the secondary system by improving the quality of detection, by combining spectrum sensing with the knowledge about the derived statistics model. In the later scheme, the secondary systems can statistically operate on the primary spectrum following the predicted occupancy distribution of the primary spectrum usage. However, such kind of coexistence will be strictly constrained by limiting the accumulative interference to the primary system under a given acceptable level.

II. Background on the Primary OFDMA System

A. OFDMA and Mobile WiMAX Basics

Mobile WiMAX uses multiple access scheme based on the Orthogonal Frequency Division Multiplexing modulation technique (OFDMA) to divide the radio bandwidth into many narrowband subcarriers orthogonally to each other.

Mobile WiMAX uses Time Division Duplex (TDD) where a Transmit Transition Gap (TTG) is added in between downlink (DL) and uplink (UL) transmissions and a Receive Transmit Gap (RTG) is added between UL and DL transmissions. An example of the structure of an OFDMA frame used in Mobile WiMAX is illustrated in Fig. 1, with frequency in terms of subchannels on the y-axis and time in terms of symbols on the x-axis. A subchannel is a logical index of a set of subcarriers in the frequency domain and a symbol is a period in the time domain. An OFDMA resource element (RE) is the allocation of a (subchannel,symbol)-coordinate in the (frequency,time)-diagram, and an OFDMA burst is a set of OFDMA REs allocated to users for DL or UL transmissions.

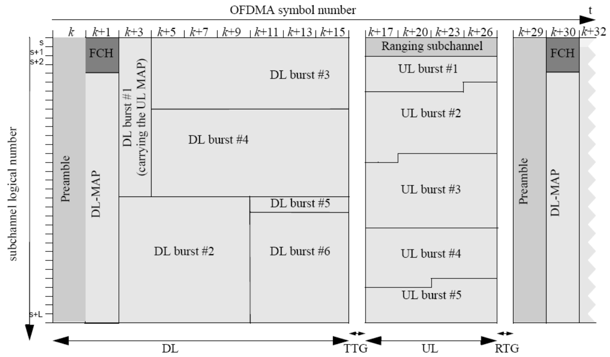


Fig. 1. IEEE802.16e-2005/WiMAX OFDMA Frame ([4],section 8.4.4.2)

The Preamble is used for synchronization, the Frame Control Header (FCH) provides the frame configuration information and the DL/UL-MAPs provide subchannel allocation and other control information for the DL and UL subframes.

B. OFDMA Scheduling Impact on White Holes

The scheduling algorithm allocates REs to bursts and bursts to OFDMA frames. The OFDMA scheduling techniques in Mobile WiMAX can be divided into three major groups. One OFDMA scheduling technique is vertical striping (Fig. 2) where the allocation is done in the frequency first, and when the last sub-channel is filled, the allocation starts from the next symbol. A second scheduling technique is horizontal striping (Fig. 2) where the resource elements are allocated in the time domain first, and when the last symbol is filled, the allocation goes on to the next sub-channel. A third scheduling technique is rectangular allocation as used in Fig. 1 where the allocation is done in both the frequency and time domain rectangularly.

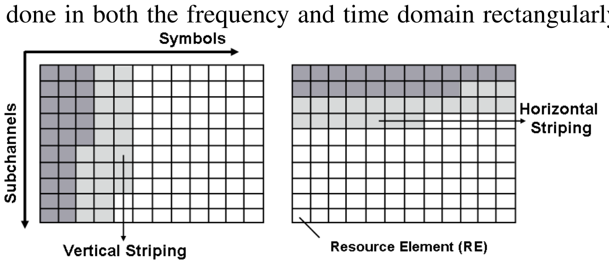


Fig. 2. Horizontal and Vertical Striping

From the secondary system perspective, vertical striping might be considered as the most suitable scheduling technique for primary systems, since the whole bandwidth can be allocated for operation over a dedicated time interval. Horizontal striping on the other hand is not that straightforward when considering the frequency domain since the subchannels are logical allocations, where the subcarriers allocated to subchannels often are distributed over the whole bandwidth. Where these subcarriers are physically located on the frequency is given by the WiMAX standard. Operator assistance might then be necessary for successful DSA operation where information is communicated between the primary and secondary systems, for instance by the ways of beaconing [10] or spectrum brokers [11]. The secondary system could preferably also use OFDM modulation to exploit all the distributed subcarriers.

III. The NS-WiMAX Simulator for Primary OFDMA Systems Simulation

A. Simulator overview and parameters setting

To simulate the primary OFDMA system, we use the well known network simulator ns-2 with an implementation of Mobile WiMAX (IEEE 802.16e-2005) by the WiMAX Forum. It is worth to notice some limitations in the current implementation. Rectangular scheduling is not implemented yet. In addition, the current version of this simulator does not support adaptive coding and modulation. It also allows only one connection per subscriber, which limits the scalability of the current implementation.

In all simulations, the general OFDMA parameters are set following the WiMAX standard as shown in Table I. The DL and UL ratios in the TDD scheme are set to 2/3 and 1/3, respectively. Partial Usage of Subchannels (PUSC) is a diversity permutation scheme that draws subcarriers pseudo-randomly to form a subchannel [4].

TABLE I
General OFDMA Parameters used in the Simulator [12]

Parameter	Value	
Channel Bandwidth (MHz) / FFT	10 / 1024	
Sampling Frequency F_s (MHz)	11.429	
Sampling Period $1/F_s$ (μs)	0.18	
Subcarrier Spacing $\Delta f = F_s/N_{FFT}$ (kHz)	10.94	
Useful Symbol Period $T_b = 1/\Delta f$ (μs)	91.4	
Guard Time $T_g = T_b/8$ (μs)	11.4	
Symbol Duration $T_s = T_b + T_g$ (μs)	102.9	
Modulation Scheme	64-QAM - 3/4 rate	
	DL PUSC	**UL PUSC**
Number of used subcarriers (N_{used})	421	409
Number of pilot subcarriers	120	280
Number of data subcarriers (Sc)	720	560
Number of data subcarriers/subchannel	24	24
Number of subchannels (N_{Sch})	30	35
Number of symobls (total 43)	28	15

The channel model used in the OFDMA module is a COST-Hata-Model combined with a Clarke-Gans implementation of Rayleigh Fading. Doppler effects are included to capture the impact of node mobility, and the Rayleigh fading channel is considered to handle the fast fading environment as described by the ITU Pedestrian A model. The path loss component is computed during the simulation, because the distance between the PUs and BS and their transmit power not are predetermined. However, the fast fading component can be computed offline prior to the simulation (1000 pre-computed channels).

B. Simulation Scenarios and Traffic Models

In this paper, we simulate a Mobile WiMAX primary base station (BS) providing data service to its Mobile WiMAX PUs. For simplicity, in our simulation scenarios, the PUs are assumed to be fixed at pre-defined locations. However, different number of PUs are set for different simulations in order to achieve more reasonable statistic traffic data. Simulations are performed with CBR traffic over UDP and for FTP traffic over TCP. Propagation effects and Quality of Service (QoS) profiles will have great impact on the modulation rate for the PUs. However, for simplicity, all the PUs are configured with the 64-QAM 3/4 modulation scheme and BE profiles.

C. Available OFDMA-Slot Capacity Calculation

The OFDMA frame capacity can be calculated by considering each OFDMA RE as one unit of capacity. The primary and secondary systems are assumed to operate in the same region. Hence, given the total number of subchannels N_{total} and symbols S_{total} in one OFDMA frame, we can simply calculate the maximum OFDMA frame capacity for each DL or UL subframe in terms of the number of REs. Thus we can derive the total and used OFDMA frame capacities as:

$$CAP_{total} = N_{total} * S_{total}, \qquad (1)$$

$$CAP_{used} = \sum_{RE=1}^{RE_{used}} RE \qquad (2)$$

The maximum available OFDMA frame capacity can easily be calculated as:

$$CAP_{avail} = CAP_{total} - CAP_{used} \qquad (3)$$

Fig. 3 illustrates our method to calculate the OFDMA frame capacity. The curves on the right graph represents how the OFDMA frame capacity is allocated along the simulation time in terms of the sequence of consecutive OFDMA frames.

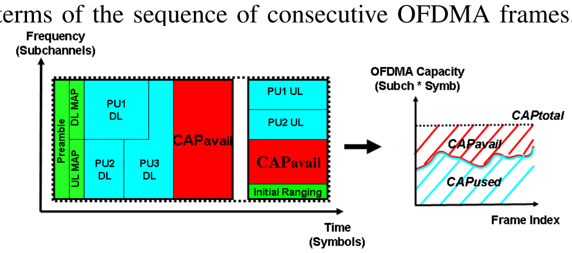


Fig. 3. Caclulation of OFDMA capactiy usage

To estimate the number of requested slots RS_i in *kbps* for each user i, we follow the approach in [13] as:

$$RS_i = \frac{RC_i}{C_{RE}} \qquad (4)$$

where RC_i is the requested capacity by user i in *bps*. The average capacity per RE, C_{RE}, in *bps/RE* is estimated as:

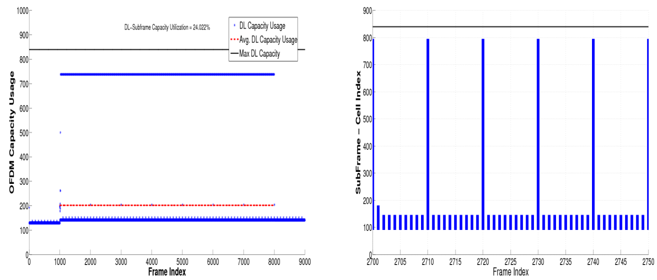
$$C_{RE} = \frac{\frac{bits}{subcarrier} \times \frac{subcarriers}{RE}}{T_{frame}} \qquad (5)$$

where T_{frame} is the OFDMA frame duration. The component $\frac{bits}{subcarrier}$ indicates the average radio access bearer efficiency in bits per sub-carrier (modulation and coding). The component $\frac{subcarriers}{RE}$ is the number of subcarriers per subchannel.

IV. Simulations Results of OFDMA Capacity

A. OFDMA Capacity for CBR traffic over UDP

In this simulation, CBR traffic over UDP between 5 PUs and the WiMAX BS is simulated to evaluate the OFDMA capacity usage. The packet size for CBR is set to 1500 bytes while the gap size between sent packets (gap_size) is 0.05 seconds, that is 20 pps (packets per second). The data traffic is simulated in the duration of 35 seconds (7000 frames). Fig. 4(a) shows the OFDMA capacity utilization in the DL subframe from this scenario. It can be seen here that several frames are allocated as much as 738 OFDMA REs during the data traffic period. However, the majority of the OFDMA frames are only assigned as little as around 150 REs. The average OFDMA capacity usage (dashed line) of the DL subframe is just about 24 % of the total REs (top solid line).



(a) Whole Simulation (b) Frames 2700 to 2750

Fig. 4. DL OFDMA Occupancy for 5 PUs with CBR traffic over UDP

In order to understand how the OFDMA capacity is allocated to each frame, we estimate the number of requested REs for each user in this simulation by using (4) and (5) as follows. First, since the 64-QAM 3/4 modulation rate is used for all PUs, the supported average symbol efficiency from each RE is the same for all PUs and can be derived as:

$$C_{RE} = \frac{4.5 * 24}{0.005} = 21600 bps/RE$$

where $\frac{bits}{subcarrier} = \frac{6 \times \frac{3}{4}}{1} = 4.5$ since 64-QAM modulates 6 bits with coding rate 3/4 onto each subcarrier, and $\frac{subcarriers}{RE}$ is given in Table I as number of subcarriers per subchannel.

As we use CBR traffic over UDP in this simulation, all 5 users are assumed to request the same OFDMA capacity, and the total requested capacity can be calculated as:

$$RC = \sum_{1}^{5} pkt\_size * pps = 5 * (1500 * 8 * 20) = 1.2Mbps$$

Thus, the number of requested REs for all five users is:

$$RS = \lceil \frac{1200000}{21600} \rceil = 56 \text{ OFDMA slots}$$

This confirms with the average in Fig. 4(a) when we add preamble, MAPs and FCH that is 3 symbols with 30 subchannels each in the DL frame ($3 * 30 = 90$), and the DL broadcast and management connections.

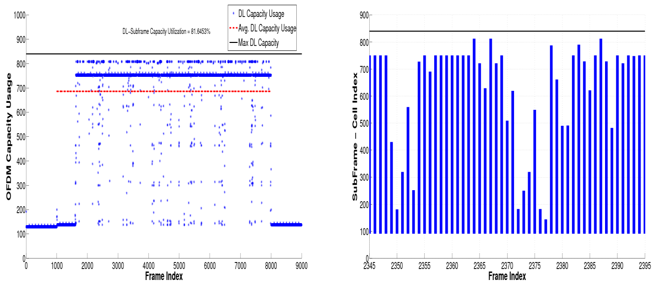
The users are configured to transmit packets at the same instant in time. Therefore these total 56 REs are requested 20 times per second and distributed over the 200 OFDMA frames allocated each second. As the result, the actual data traffic requested by the users is allocated for every 10th OFDMA frames as illustrated by the snapshot from frame 2700 to 2750 in Fig. 4(b), and can mathematically be described by

$$\frac{gap\_size}{T_{frame}} \times RS = \frac{0.05}{0.005} \times 56 = 560 \qquad (6)$$

This confirms with the results in Fig.4(b) when we add the occupied REs for the preamble, MAPs and FCH in addition to management and broadcast connections as before.

B. OFDMA Capacity for FTP traffic over TCP

FTP traffic over TCP for is more complex to model than the CBR scenario due to a more advanced transport protocol with functionality such as TCP window size and algorithms for congestion control. Simulations were performed with FTP traffic over TCP for 3 users, configured with capacity unlimited BE profiles. It can be seen that the OFDMA capacity utilization plotted in Fig. 5 varies more than in the CBR case above, and the total utilization of 81.65 % is also higher.



(a) Whole Simulation (b) Frames 2345 to 2395

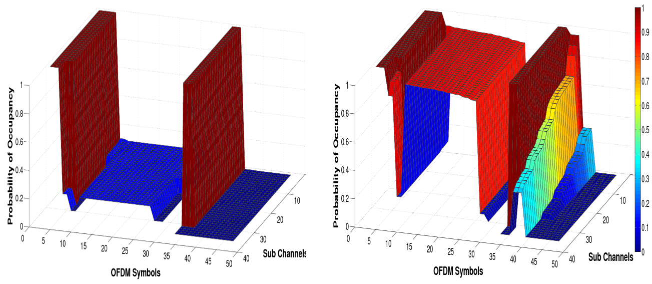
Fig. 5. DL OFDMA Occupancy for FTP over TCP

The capacity utilization is lower at the beginning of the FTP traffic scenario than in the CBR scenario, which is due to the well known slow start part of the congestion control strategy in TCP. The lower utilization in some of the frames is probably due to the congestion avoidance functionality in TCP, where the TCP window size is lowered before an increase starts.

V. Simulations Results of OFDMA Spectrum Occupancy Distribution

As mentioned earlier, we are interested in designing a DSA scheme for the secondary systems, which exploit unused spectrum in the primary OFDMA system. The first step towards this objective is to understand how the OFDMA REs in each OFDMA frame is distributed over time. We therefore estimate the occupancy distribution of the OFDMA REs over a consecutive sequence of the OFDMA frames, and derive average occupancy map of the OFDMA frames.

The occupancy probability of each OFDMA RE is calculated as the percentage of the total number of simulated OFDMA frames on which the OFDMA RE is occupied. The OFDMA occupancy distribution maps are represented by a three-dimension temperature map as shown in Fig. 6, where x-axis and y-axis represent the OFDMA symbol and subchannel dimensions of the OFDMA frame. The z-axis and temperature colors in the scale rom $0 - 1$ represents the occupancy probabilities of the REs.



(a) 5 PUs with CBR traffic (1500,20) (b) 3 PUs with FTP traffic

Fig. 6. Average OFDMA occupancy distribution as the temperature map.

The temperature map in Fig. 6(a) illustrates the general occupancy distribution of the frame for CBR traffic between 5 PUs and the primary BS. The first three symbols are fully allocated to the preamble, FCH, and DL/UL MAPs. Part of the second and third symbols are also fully allocated to management and broadcast bursts. Obviously, in this type of data traffic scenario, the majority of consecutive OFDMA REs are not allocated as represented by the light blue temperature indicating a very low occupancy probability at 10%. On the other hand, the temperature map for 3 users with FTP traffic and unlimited bitrate profiles in Fig. 6(b) shows a much higher occupancy probability throughout the frame.

VI. Designing the Secondary System

A. Sensing Techniques to Detect Available OFDMA Spectrum

Sensing techniques are generally divided into the three major categories [14]; Matched filter, Energy Detection and Cyclostationary Feature Detection. Yucek et al. also add Waveform based sensing and Radio Identification based sensing in [15]. A problem with the mentioned sensing methods is that the signal might be too weak to be detected, and cooperative sensing among several sensing nodes is considered to increase detection reliability. Dependent on the secondary system design the sensing might introduce overhead, and the sensing strategy used is therefore important concerning sensing frequency and sensing time.

Available periods in the time domain in OFDMA systems can simply be detected when vertical striping is used, but available frequency is more complex to detect due to the subcarrier distribution as discussed in Section II. A strategy could therefore be to utilize the first symbol after the latest partially occupied symbol. Sensing frequency could then be intense until this symbol is detected and close to zero for the rest of the subframe. Such a scheme could be implemented with all sensing methods, and the secondary system capacity could be calculated by using Eq. (3) with Eq. (1), but Eq. (2) should only count used symbols so that $CAP_{used} = N_{used} * S_{used}$, where N_{used} and S_{used} are the number of subchannels and symbols used by the primary system, respectively.

Detection of white space in the frequency domain would require huge amounts of sensors for 1024 subcarriers in a 10MHz channel. An alternative is to use CR-OFDM [16] in order to detect the subcarrier occupancy. This could be combined with the more advanced detection techniques. For such a scheme, the optimal secondary system capacity for both frequency and time domain can be calculated by using Eq. (3) with Eq. (1) and (2). However, these calculations should be considered with a complete sensing strategy with sensing frequency, sensing time, probability of detection (p_d) and probability of false alarm (p_f).

B. DSA Scheme based on Statistics about Primary OFDMA System

Quality of Detection (QoD) is important for secondary system performance, but it will be useful to estimate spectrum usage of PUs in multiple dimensions and develop algorithms for prediction into the future by using past information. Such information could either be based on sensing or operator assistance. The latter is the preferable in the sense that accurate information is achieved. Optimally, the operator would send real time information about scheduling and spectrum usage to the secondary system. Another way could be that the operator assisted by using beaconing, which would be simple for vertical striping where a beacon should be sent at the beginning and end of white spectrum holes. Real-time communication with the operator is challenging and utilization of statistics and future predictions of primary system usage should be investigated further.

Therefore, we tend to use the statistic models of the primary spectrum occupancy in order to develop and implement DSA schemes that make use of the statistics of the spectrum occupancy. The DSA scheme should be optimized to utilize as much available capacity as possible while limiting interference caused to the primary system under an acceptance level given by the primary system or regulatory.

The DSA scheme can be combined with an idea based on operator assistance, where the operator assist by applying more robust coding on parts of the OFDMA frame. With vertical striping, more robust coding could be added on the last consecutive OFDMA symbols in the OFDMA subframe in order to reduce the impact of harmful interference caused by the secondary system. Obviously, the primary operator must offer some energy, but it could generate additional revenue.

Another idea is to design a random DSA scheme, which models the random access behavior of the secondary system to the primary spectrum. In this scheme, it is assumed that the secondary traffic arrivals follow the Poisson distribution. Hence, this random DSA scheme can model and estimate the maximum capacity gain that the secondary system could achieve by exploiting the statistics of the primary spectrum, while guaranteeing the interference under a given threshold.

A complete secondary system would use a combined approach, where the DSA scheme is based on statistics about OFDMA occupancy and a sensing technique is applied to detect PUs in real time to reduce the probability of interference.

VII. CONCLUSION

We have simulated and characterized spectrum occupancy in primary networks utilizing the popular and emerging transmission technique OFDMA. The network simulator tool ns-2 was used with an implementation of Mobile WiMAX to simulate the primary OFDMA system. Next, we proposed ideas and directions on access schemes for DSA systems based on these characterizations. We conclude that it should be possible to utilize white holes in a mobile broadband OFDMA system, but that the OFDMA scheduling technique and the traffic models used by primary users will have significant impact on the characterization of spectrum occupancy. Operator assistance is also considered as important in order to maximize the secondary system utilization of the available OFDMA capactiy.

Future work will first be to model the primary system with a more realistic mixed traffic scenario representative to derive complete models for primary OFDMA occupancy, and then to implement the ideas for DSA schemes proposed in this paper.

REFERENCES

[1] FCC, "Spectrum policy task force report," Tech. Rep. ET Docket No. 02-155, Nov. 2002.
[2] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 79–89, May 2007.
[3] H. Yin and S. Alamouti, "Ofdma: A broadband wireless access technology," *Sarnoff Symposium, 2006 IEEE*, pp. 1–4, March 2006.
[4] "Ieee standard for local and metropolitan area networks part 16: Air interface for fixed and mobile broadband wireless access systems amendment 2: Physical and medium access control layers for combined fixed and mobile operation in licensed bands and corrigendum 1," *IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor 1-2005 (Amendment and Corrigendum to IEEE Std 802.16-2004)*, pp. 1–822, 2006.
[5] T. Weiss, J. Hillenbrand, A. Krohn, and F. Jondral, "Mutual interference in ofdm-based spectrum pooling systems," *Vehicular Technology Conference, 2004. VTC 2004-Spring. 2004 IEEE 59th*, vol. 4, pp. 1873–1877 Vol.4, May 2004.
[6] T. Weiss and F. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *Communications Magazine, IEEE*, vol. 42, no. 3, pp. S8–14, Mar 2004.
[7] S. Geirhofer, L. Tong, and B. Sadler, "Cognitive radios for dynamic spectrum access - dynamic spectrum access in the time domain: Modeling and exploiting white space," *Communications Magazine, IEEE*, vol. 45, no. 5, pp. 66–72, May 2007.
[8] S. Geirhofer, L. Tong, and B. M. Sadler, "Interference-aware ofdma resource allocation: A predictive approach," *Military Communications Conference, 2008. MILCOM 2008. IEEE*, pp. 1–7, Nov. 2008.
[9] "The network simulator ns-2." [Online]. Available: http://www.isi.edu/nsnam/ns/
[10] A. Hulbert, "Spectrum sharing through beacons," vol. 2, Sept. 2005, pp. 989–993 Vol. 2.
[11] M. M. Buddhikot and K. Ryan, "Spectrum management in coordinated dynamic spectrum access based cellular networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 299–307. [Online]. Available: http://dx.doi.org/10.1109/DYSPAN.2005.1542646
[12] H. Yaghoobi, "Scalable ofdma physical layer in ieee 802.16 wirelessman," *Intel Technology Journal*, vol. 8, no. 3, pp. 201–212, 2004.
[13] D. López-Pérez, A. Jüttner, and J. Zhang, "Optimisation methods for dynamic frequency planning in ofdma networks," *In IEEE Networks*, pp. 1–28, Oct. 2008.
[14] D. Cabric, S. Mishra, and R. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," vol. 1, Nov. 2004, pp. 772–776 Vol.1.
[15] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys & Tutorials, IEEE*, vol. 11, no. 1, pp. 116–130, Quarter 2009.
[16] H. Mahmoud, T. Yucek, and H. Arslan, "Ofdm for cognitive radio: merits and challenges [accepted from open call]," *Wireless Communications, IEEE*, vol. 16, no. 2, pp. 6–15, April 2009.

Paper B
Evaluation of Business Cases for a Cognitive Radio Network based on Wireless Sensor Network

Ole Grøndalen, Markku Lähteenoja and Pål Grønsund

Proceedings of the 5th IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (IEEE DySPAN), Aachen, Germany, May 3-6, 2011.

Evaluation of Business Cases for a Cognitive Radio Network based on Wireless Sensor Network

Ole Grøndalen, Markku Lähteenoja and Pål Grønsund
Telenor ASA
Snarøyveien 30, 1331 Fornebu, Norway
{ole.grondalen, markku.lahteenoja, pal.gronsund}@telenor.com

Abstract—**This paper proposes and evaluates three business case scenarios for deployment of a sensor network aided cognitive radio system in a typical European city. The first and main business case is based on spectrum sharing, where several spectrum owners establish a joint venture and this joint venture gets the rights to use the "unused" spectrum resources of all those spectrum owners in a cognitive way. Then we study the business case of a spectrum broker, an entity that deploys, builds and operates a sensor network and sells either sensing information or information on spectrum opportunities to one or more cognitive radio operators. Finally we analyze the potential of a new entrant without existing infrastructure or frequency licenses, that uses a sensor network aided cognitive radio system to offer a nomadic mobile broadband service. It is found that the spectrum sharing business case is one of the best possible cases for the studied system because the joint venture operator has free access to frequency resources of the mother companies, detailed knowledge of the primary systems and good possibilities for sharing infrastructure with the owning operators. However, since the studied system is an innovative concept and some of the assumed parameters are therefore uncertain, it should be noted that the main value of the business case calculations is to identify critical aspects influencing the profitability so that future research and development work can focus on them. It is found that the most critical aspects are the fixed sensor density, the fixed sensor operational costs and the number of new cognitive base station sites required.**

Keywords: cognitive radio, business case, sensor network, spectrum sharing, spectrum broker, new entrant

I. INTRODUCTION

Most research and development work on cognitive radio (CR) focuses on pure technical aspects of the technology. However, in order for an operator to be interested in deploying CR based networks the anticipated costs must be in proportion to what the users are realistically willing to pay for the service. Hence, techno-economical studies should be done in parallel with the technical research and development work to ensure that the solutions found are both technically and economically viable.

Since CR is an open and relatively new research field, there is a lot of uncertainty associated with many of the parameters needed in business case analyses. But even with uncertain input parameters the business case studies can be used for identifying critical parameters that must be considered in the technical studies. A good way to proceed towards a viable solution is to do the business case calculations and technical calculations iteratively, each time using the latest results of one to derive the input parameters to the other.

In this paper we study business cases for a sensor network aided CR scenario [1] that consist of three main networks; a primary network, a secondary CR network, and a sensor network which might be a separate network and also embedded in the cognitive network. Three business cases are studied, where the target scenario is for providing a wireless broadband service in urban and suburban areas. The first business case entitled "Spectrum Sharing" is an extended version of the business case proposed in [2], with more extensive research behind the business case assumptions and parameters, updated results, more details about the model used and the business case ecosystem. This paper also study a second business case entitled "Spectrum Broker" which is based around the concept of a an entity that deploys, builds and operates a sensor network and sells either sensing information or information on spectrum opportunities to one or more CR operators. The concept of a spectrum broker has previously been proposed and studied in [3] and [4], but to the authors best knowledge there does not exists any business case proposal for this concept. The third business case proposal entitled "New Entrant" study the potential of a new entrant without existing infrastructure or frequency licenses, that uses a sensor network aided CR system to offer a nomadic mobile broadband service.

The rest of this paper is organized as follows: An overview of the Sensor Network Aided Cognitive Radio (SENDORA) system is given in Section II. The SENDORA ecosystem is described in Section III and the model for analysis and ecosystem evaluation is described in Section IV. Assumptions behind the business cases are described in detail in Section V before the results for the three business cases are presented in Section VI, VII and VIII. The paper is concluded in Section IX.

II. OVERVIEW OF THE SENSOR NETWORK AIDED COGNITIVE RADIO SYSTEM

A. System Overview

The SENDORA technology utilizes wireless sensor networks (WSNs) to support the coexistence of licensed and unlicensed wireless users in an area, and the SENDORA scenario is constituted by three main networks; the primary network, the secondary network and the sensor network. The general architecture of the SENDORA system is depicted in Figure 1, where the network of cognitive users, called the secondary network, first communicates with the wireless sensor network. The wireless sensor network monitors the

This paper presents results of a study conducted within the EU FP7 project SENDORA [1] for a sensor network aided cognitive radio system.

spectrum usage, and is thus aware of the spectrum holes that are currently available and can potentially be exploited by the secondary network. This information is provided back to the secondary network. The secondary users are then able to communicate without causing harmful interference to the licensed network, called the primary network.

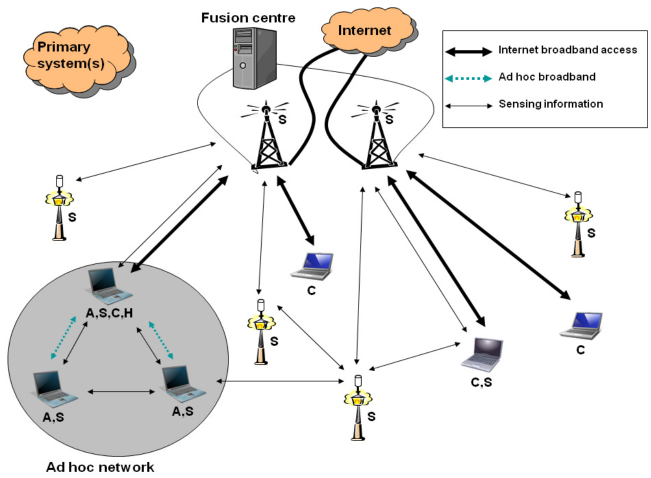


Figure 1. General SENDORA scenario

The sensor network aided approach will significantly improve the system's ability to detect primary users compared to CR solutions based only on sensing performed by terminals. The sensor network will consist of an externally deployed sensor network and possibly sensing capabilities embedded in user terminals. The external sensor network makes it possible to guarantee that primary users will be detected with a specified probability regardless of the number of CRs present in the area. Additionally, embedded sensing in terminals can enhance system performance by providing more local sensing information from the areas where the CR users are located and sensing will be improved as the number of cognitive users grows. The sensor network can also be used to measure the interference generated by the CR system. This can be used to control the interference generated to ensure both protection of primary systems and optimal use of spectrum holes.

The target scenario for the SENDORA systems is for providing a nomadic wireless broadband service in urban and suburban areas. The systems will be best suited to provide non-real-time services like web browsing and video downloading. Real-time services like telephony and video streaming can be provided occasionally, but the operator will usually not be able to give strict quality guarantees for such services.

B. System Architecture

The system architecture depicted in Figure 1 consists of three parts: the communication architecture and the sensing architecture which are connected together by the fusion centre.

1) Communication Architeceutre

The Fusion Centre is a functional entity that receives sensing data collected through the sensor network and estimates the spectrum usage situation in the area covered by the sensor network based on this information. The fusion centre also communicates with the communication network providing it with the information it needs to operate cognitively in an optimal way. Ad-hoc networks can also be part of the SENDORA network, but will not be considered in the business case proposed here. The terminals are marked with *C*, *A* and *S* according to their functional capabilities and *H* if they are locally cluster heads in an ad-hoc network:

- **Centralized access (C)**: Terminal has the properties needed to communicate with the BSs
- **Ad hoc (A)**: Terminal has the properties required to establish and be part of an ad hoc network.
- **Sensing (S)**: Terminal has sensing capabilities.

2) Sensing Architecture

The sensing architecture consists of a fixed network of sensors complemented with sensing capabilities integrated in some of the terminals. The reason for having a fixed network of sensors is that it is difficult to base the operation of a CR network solely on information from sensing integrated in user terminals. The number and positions of the terminals will be random variables and sometimes the sensor network formed by the terminals will not be able to detect primary users with the required confidence. By deploying a fixed and dedicated network of sensors where the number and location of the sensors are carefully chosen, a certain primary user detection confidence can be guaranteed. A fixed deployed sensor network also has the advantage that the sensors can communicate with each other and eventually with one or several fusion centers through a wired backbone network. Sensors can be powered from the mains.

On the other hand, sensing integrated into the terminals will be co-located with the CRs and hence be capable of providing accurate local information. By using this information in addition to information from a fixed deployed sensor network, the CR network can be controlled in a much better way. Primary users close to the user, which are the ones that will experience the most serious interference from the CR terminal, will be detected much faster by the integrated sensor than by the fixed sensor network.

3) Fusion Centre

The fusion centre functionally connects the sensor network and the communication network and acts as an aggregation point for the data from the sensors in the sensor network. Based on the sensor data received, the fusion centre estimates the spectrum usage in the geographical area covered by the sensor network. A CR network might have more than one fusion centre which will communicate with each other and share information about the spectrum situation in their areas and their own network's usage of spectrum resources.

III. SENDORA Ecosystem

Ecosystem considerations for the sensor network aided CR system are presented in this section, with the chosen scenario: "Nomadic broadband in urban and suburban areas" as the basis for these considerations. The word "ecosystem" in this context mean business modeling [5] including the roles of the actors, relations (like partnership) between the actors, cost and revenue structures and money flows between the actors. Specific business cases can then be used to quantify the value of different ecosystem options. For related work; Chapin and Lehr studied interlinked technical and economic issues associated with markets for DSA-based wireless services in [6].

The studied system is an innovative concept with a long term focus, and therefore the related ecosystem is unproven in real market conditions. There will be several actors (see section III.B), that may not always have the same interests and expectations. The requirement for a successful and functional new ecosystem is that the (main) actors have sufficient incentives to be part of that ecosystem. The most important and sometimes the only incentive, at least for the commercial actors, is simply the money i.e. the economical results for the company in the short and long term.

This ecosystem will include mostly actors, which have economical profit as their main motivation, but it can also include actors like regulators, which can have other motives, like for instance welfare of the society as a whole, fairness and a wish to increase competition in the telecommunication. To create a functional SENDORA ecosystem will be a challenging task with many uncertain aspects.

A. *Ecosystem Roles*

SENDORA ecosystem will include both traditional roles in the communication business and some new roles specific only for the SENDORA ecosystem. At least the following roles can be foreseen in the ecosystem for the sensor network aided CR in the chosen scenario:

1. End user of the communication applications
2. Owner of the license for the radio spectrum
   - Existing mobile and/or fixed telecom operators
   - TV broadcasters
   - Public authorities (such as police, health care, aviation)
   - Military organizations
3. CR operator that will utilize a radio spectrum licensed to others
   - As in point 2 above
   - New operators
4. Regulatory body
5. Spectrum broker
   - Regulatory body
   - Owner of the license for the radio spectrum
   - Independent third party
6. Owner of the sensor network
7. Hardware and software vendor
   - CR elements
   - Sensor network elements
8. System integrator

There is a clear difference between roles and actors in the ecosystem. One specific real actor (company) can have several roles in the SENDORA ecosystem. As an example, an existing mobile operator can simultaneously be a spectrum owner, CR operator, owner of the sensor network and spectrum broker.

B. *Ecosystem Actors*

The different actors in the future SENDORA ecosystem will have varied motivations why they will be part of this ecosystem. In the sequel follows a discussion of what could be the motivations of different actors.

1) End users of (telecommunication) services

In principle, the normal end user (person) does not care about technology. What matters to the end user is the price and quality of the services provided. The CR or SENDORA system is mostly invisible to the user and has only indirect influence to the user. It can make possible better and more affordable services trough technology advancements and increased competition between service providers.

One special user group in the SENDORA ecosystem could be technologically advanced users, that could remove the need for a network operator by having own ad-hoc networks to provide nomadic broadband for a limited user group. This requires advanced technical skills and also coordination (regarding terminals, software etc) between the users.

2) Existing (mobile) operators

Mobile operators can have many roles (spectrum owner, CR operator, broker, owner of the sensor network) in the SENDORA ecosystem. They can have defensive motives (e.g. to hinder that cognitive operation disturbs their primary operation, to protect their valuable assets in already acquired spectrum licenses), but they can also have offensive motives (e.g. earning money on SENDORA spectrum trading, improving their own operation by SENDORA system, being themselves CR operators in new areas).

3) TV broadcasters

TV broadcasters are important spectrum owners, and they will avoid that the new systems disturb their TV distribution. As for other spectrum owners, SENDORA spectrum trading is an earning opportunity for the TV broadcasters.

4) Public authorities

Public authorities (e.g. police, fire brigades, health care, aviation and military) are on the other hand spectrum owners, but they could also be CR operators. For them one important application could be high quality ad hoc networks during large accidents or military actions.

5) New operators

CR operation is one possibility for new operators to enter the market. In the mobile business until now the ownership of the spectrum license has been crucial and expensive part of the business model. The potential new operators are clearly interested in getting a reasonable priced access to spectrum by the SENDORA system.

6) Regulatory body

Regulatory bodies have interest to all technologies that can improve the utilization of the radio spectrum. The spectrum relevant for telecommunication purposes is a limited and therefore expensive resource. The opportunistic use of radio spectrum is not yet scheduled in Europe (it has been allowed in TV white spaces by FCC in the US [7]), but it may be needed soon to open some bands to cognitive operation considering the future need for bandwidth. Today's approach consists in dividing the spectrum into small pieces, each for a specific purpose and the applications use their spectrum to a limited extent, which leads to the unwanted situation of under-utilization of this scarce resource. Regulation authorities recognize that this approach is reaching its limits.

One of the key issues for the regulation is how to control interference among systems. In the SENDORA ecosystem, the regulation may be provided interference measurement means thanks to the WSN approach. The WSN could even be owned by the regulator.

7) Vendor

Vendors are also key actors in the ecosystem. Base stations (BSs) and terminals require some new capabilities to allow CR operation, and especially WSN-aided CR operation. In particular, hardware platforms must be flexible enough to support communications in several frequency bands and will be based on a Software Radio approach. In the ecosystem, the vendors must be given the opportunity to sell a sufficient quantity of stations and terminals with enough margins.

C. Examples of SENDORA ecosystems

SENDORA ecosystems can have different grade of complexity. The simplest SENDORA "ecosystem" is the case where one actor, such as a mobile operator with a variety of spectrum resources, will use CR for better utilization of its own spectrum to provide new services. An extension of this is a "spectrum sharing" case (see section VI), where spectrum owners form a joint venture that gets rights to use the "unused" spectrum of all those spectrum owners in a cognitive way. Minimal coordination and interaction with other actors is needed for such ecosystems.

The more complete SENDORA ecosystem can include spectrum trading between the spectrum owners and the new cognitive operators. This trading can be replaced by regulatory decisions to regulate the access to the spectrum. One possible important new role in this kind of ecosystem will be the broker role, often a regulatory body or an independent third party, that will ensure fairness in the interactions. This kind of ecosystem is more complicated to create, because it may require coordination, trust and interaction between actors, which even may have conflicting motivations for participating. Detailed rules governing the CR operations have to be developed. The broker (Section VII) and new entrant (Section VIII) cases are the first attempts to analyze these aspects.

IV. Business case Analysis and Ecosystem Evaluations

SENDORA is an innovative concept and much research and development remains before commercial applications will appear. Therefore the input data to the SENDORA business cases is uncertain and the results from the business case calculations can only give indications, not yet definite answer or strong conclusions. The main value of SENDORA business case calculations is to identify critical aspects for SENDORA profitability, so that technical R&D work can focus on them.

The traditional cash flow analysis will be used to get an indication of the profitability. The cash flow means income (revenues) subtracted by cost (investments and operational costs) for a given time period. Due to large uncertainties the cash flow analysis must be enhanced with sensitivity analysis. Sensitivity analysis is done by changing the value of one (critical) input parameter and showing how the economical results are changing.

Several economical concepts are used in the business case analyses in this document. These are summarized below:

ARPU (Average Revenue Per User)

CAPEX (Capital expenditures) is expenditures associated with the implementation or extension of fixed assets. There is a residual value associated to these expenses. Investment is often used as an identical term to CAPEX.

OPEX (Operational expenditures) is defined as expenditures necessary for running the business or the equipment, indispensable to keep the services active and running. Once made, these expenses have no residual value.

EBITDA (Earnings before interests, taxes, depreciation and amortization) = Revenues – OPEX. This measure is often used to estimate the operational efficiency.

NPV (Net present value) is the sum of a series of cash flows (revenues subtracted by costs), when discounted to the present value:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{A_t}{(1+p)^t}$$

where p is the annual discount rate, At the payment in year t and n the lifetime of the project. *NPV* is the most important criteria when defining the profitability of the project.

Discount rate is the rate used for discounting amounts to other points in time as in the calculation of NPV. It reflects the inflation and the fact that the estimated amounts in the future carry significant uncertainty. Typical values of discount rate are around 10%.

IRR (Internal rate of return) is the discount rate, that gives NPV = 0. The higher the IRR is, the better the project is. Assuming all other factors are equal among various projects, the project with the highest IRR would probably be considered the best.

Payback period is the amounts of years that it takes to have the accumulated revenues equal the accumulated costs (CAPEX and OPEX).

These concepts are not necessarily always unambiguous; there can be slight variations and different interpretations. More information about economical terms can be found in [6].

V. Business Case Assumptions

A. General assumptions

The business case is calculated for a hypothetical western European city with 1 million inhabitants and with an area of 200 km^2. The city has a downtown area which covers 50 km^2. All calculations will be made for this city, but can with some effort be scaled up and down for larger and smaller cities.

The studied city is assumed to have a well developed telecommunication market. This means a high penetration of both mobile (voice, data and broadband) and fixed telecommunication services and also TV services. A working competition environment with several network owners and service providers is assumed.

The commercial realization of SENDORA technologies lies some years ahead. To allow for this, the study period is assumed to be from 2015 to 2020. This adds some more challenges to the study, since the technological developments and other development related to the telecom industry in the years from now (2010) to 2015 must be anticipated.

A traditional cash flow analysis will be used to get an indication of the profitability. The discount rate used in the calculations is 10%. Due to large uncertainties the cash flow analysis will be enhanced with sensitivity analysis. The basis target scenario business case calculation can be described with:

- **Service provided**: Nomadic broadband in urban and suburban areas, mostly non-real time services (best effort).
- **Sensing architecture**: Both an externally deployed network of fixed sensors and embedded sensing capability in the terminals (integrated sensors).
- **Communication architecture**: The communication architecture consists of a centralized network of BSs through which the terminals can get Internet access, complemented by terminals communicating directly between each other forming local ad hoc networks. This study will only consider the centralized part of the architecture, i.e. communication via BSs. There may be local ad hoc networks, but these are assumed not to affect the business case.

Deployment of the CR network in the city will be done in three stages. The network for the downtown area (50 km^2) will be deployed in 2015, and the network in the suburban area in 2016 (75 km^2) and 2017 (75 km^2).

B. Revenue Assumptions

1) Revenues From Subscriptions

To estimate the subscription fee that can be charged for the SENDORA service, we will compare to the corresponding fee for mobile broadband services. The main use of both the SENDORA service and the mobile broadband service will be for providing Internet connectivity for different types of terminals. However, the SENDORA service will have inferior QoS support and will not support mobility. On the other hand, the SENDORA service can offer higher peak capacities when sufficient spectrum is available and better coverage (including indoor coverage) since it can use a larger range of frequencies. But all in all, the SENDORA service is clearly a somewhat lower grade service than mobile broadband, and hence its subscription rates should also be somewhat lower.

To find what a typical mobile broadband subscription rate could be, a simple survey of prices offered was done in a set of European countries in June 2010. The minimum and maximum subscription rates are 23.90 and 38.00 € / month respectively. The average rate is 31.9 € / month.

We will assume that there is a moderate yearly reduction of the subscription fee. This reflects the trend that the operators often choose to increase the performance parameters such as the throughput and data allowance, and keep the fees fixed. However some reduction should still be expected due to the competition. We will assume an average yearly reduction of the subscription fees of 2%. We thus expect the average mobile broadband subscription fee to be about 28.7€ in 2015.

To determine exactly how much lower the subscription rate for the SENDORA service will be, is of course very difficult. Hence any estimate will be very uncertain. We have chosen to assume a subscription rate for the SENDORA service of 20 € / month in 2015. This is about 30% lower than the expected average mobile broadband subscription fee. In reality there are important dependencies, like price elasticity between the mobile/nomadic broadband services from the other operators and the nomadic broadband services from the joint venture (i.e. if one operator increase its tariffs, it will get less users because of competition). These aspects are complicated and not taken into account in the business case calculations.

As the model for the number of customers we will assume that the joint venture has 10,000 subscribers in 2015 (end of the year) and 100,000 subscribers in 2020. Since we assume that the city has 1 million inhabitants, this corresponds to assuming that 10% of the city's population are subscribers of the joint venture operator in 2020. It is assumed that the number of subscribers as a function of time follows an S-curve often referred to as a generalized logistic curve or Richard's curve. The number of subscribers at the end of each year in the study period is given in Table 1.

TABLE 1. NUMBER OF SUBSCRIBERS AT THE END OF EACH YEAR

Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
#subscribers	10 000	25 785	40 894	59 951	80 654	100 000

2) Revenues from selling sensor information

The joint venture can also get income from selling sensor information to for instance other companies, the regulator or public authorities. Some examples of data that can be sold are:

- Electromagnetic field strength measurements to monitor the exposure people in the area experience to such radiation.
- Measurements of pollution level (e.g. to detect illegal emissions from factories in the area)
- Weather data (temperature, air pressure, wind speed, precipitation, etc.)
- Spectrum holes (not utilized by the joint venture)

The addition of such measurement capabilities can increase the price of the sensors. We will not assume any income from selling sensor information in the studied business cases.

C. Sensor network related assumptions

The sensor network related assumptions consists of the costs related to purchasing and operating the fixed sensor network and the fusion centre, and the possible costs for subsidizing user terminals with sensing capabilities. To calculate the CAPEX and OPEX for the fixed sensor network, it is necessary to know the number of sensors needed or equivalently the required fixed sensor density.

1) Required sensor density

One of the most important parameters for SENDORA systems is the required fixed sensor density. This parameter again depends on other parameters, like what sensing technology is used, what primary systems that must be detected and the regulatory requirements. Sensor density was especially studied in [10].

The fixed sensor density used in the business cases is based on results for a case study with LTE as the primary system. The parameter input set for the study is given in Table 2. Two input parameter sets are considered since the exact value of many of the input parameters is not known. The strict parameter set includes parameters that make sensing more challenging, while the loose parameter set relaxes some physical constraints and requirements.

TABLE 2. PARAMETER INPUT SET FOR THE LTE CASE STUDY

Case Study	LTE Strict	LTE Loose
Channel Model Parameters		
Path-loss exponent	4	3.5
Tot. AWGN on sensed band	-96dBm	-100dBm
Lognormal zero-mean shadowing	5dB	5dB
Primary System Parameters		
Signal Bandwidth	5MHz	5MHz
Signal Power	24dBm	24dBm
Max. prob. of interference	10^{-6}	10^{-3}
Interference radius	400 meter	300 meter
Design Parameters		
Sensing Bandwidth Unit	200kHz	200kHz
Sampling Frequency	400kHz	400kHz

The following measures are defined:

- **Cognitive capacity**: is the portion of narrow band bandwidth one cognitive user receives. For example, a cognitive capacity of 50% means 100 kHz bandwidth per cognitive user.
- **Probability of interference**: the probability that a channel used by the primary system is miss-detected and allocated for a cognitive user.

Furthermore, the following description of the networking environment applies:

- Primary system load is characterized by the probability that a channel is used.
- All sensors sense the same set of channels.
- Channel allocation in the secondary system is modeled by the fair sharing of channels that are detected free.
- Interference control is characterized by the interference radius, which is the minimum distance of primary and secondary transmitters, such as no primary receiver experiences interference, assuming fixed transmission power at both the primary and the secondary transmitters. Interference happens if a secondary transmitter within this radius transmits on the channel that is used by the primary system.

The fixed sensors density required depends on density of user terminals. As the density of user terminals increase, they will provide more sensing information through their integrated sensing capability. But since capacity demand also increases with increasing user terminal density, more accurate sensing data is required. The obtained results for the strict and loose LTE scenarios are given in Table 3 and Table 4 respectively. To optimize the business case the number of sensor sites should be minimized. As can be seen from Table 3 and Table 4, minimum number of fixed sensors occurs when the cognitive user density is about 75 and 35 users/km^2 respectively.

TABLE 3. REQUIRED FIXED SENSOR DENSITY FOR DIFFERENT COGNITIVE USER DENSITIES FOR THE LTE STRICT CASE. PRIMARY SYSTEM LOAD IS 10% AND COGNITIVE CAPACITY 10%. ALL USER TERMINALS HAVE SENSING CAPABILITY.

Secondary User Density [users/km^2]	Fixed sensor density [sensors/ km^2]
10	120
25	122
50	90
75	75
100	125
150	170
200	220
300	450

TABLE 4. REQUIRED FIXED SENSOR DENSITY FOR DIFFERENT COGNITIVE USER DENSITIES FOR THE LTE LOOSE CASE. PRIMARY SYSTEM LOAD IS 10% AND COGNITIVE CAPACITY 55%. ALL USER TERMINALS HAVE SENSING CAPABILITY.

Secondary User Density [users/km^2]	Fixed sensor density [sensors/ km^2]
5	10.5
10	8
15	5
25	4.5
30	4
35	1
40	6
50	25
100	52

In order to minimize the required fixed sensor density, the users can be divided into groups using different and disjoint sets of frequencies. The number of users in each group should be optimized such that the number of fixed sensor sites is minimized. For example, using the strict LTE results, if the number of users is 300 they can be divided into 4 groups each having 75 users. Each group uses a different set of frequencies, so they can be seen as 4 independent groups operating in parallel. Hence, from Table 3 it can be seen that it is sufficient to have 75 fixed sensor sites. However, at each site there must be sufficient sensing capacity to cover all 4 sets of frequencies.

Figure 2 shows for the strict LTE case the minimum density of fixed sensor sites as a function of the secondary user density for a targeted cognitive capacity of 10%. The relationship between user density and fixed sensor density has been calculated from Table 3 by using linear interpolation. The corresponding curve for the loose LTE case is shown in Figure 3. As can be seen from Figure 2, the required fixed sensor density for the strict LTE case is highest when the secondary user density is low. At each multiple of 75 users/km^2, the required fixed sensor density takes its minimum value of 75 sensors/km^2. In between these multiples, the fixed sensor density has local maxima which become lower as the secondary user density increases.

The number of cognitive terminals in an area varies randomly. The number shows both short term variations from one minute to the next as users enter and leave the area, medium term variations from high values during peak hours to low values during silent periods and long term variations from low values right after the network has been deployed to higher numbers as the operator gets more customers. The dimensioning of the fixed sensor network must be done in such a way that primary systems are given the required protection at all times. Hence, generally it is the maximum values shown in Figure 2 and Figure 3 that should be considered.

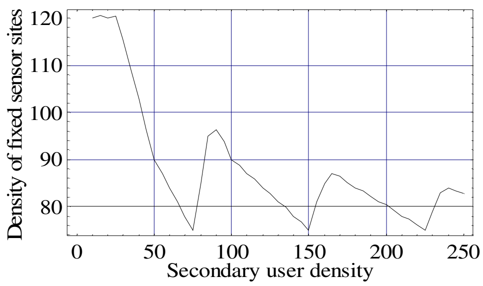


Figure 2. Required fixed sensor density (sensors/km2) as a function of secondary user density (users/km2) for the strict LTE case.

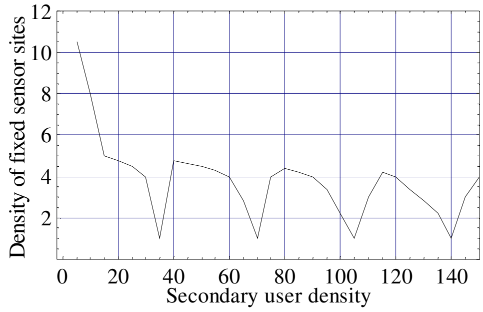


Figure 3. Required fixed sensor density (sensors/km2) as a function of secondary user density (users/km2) for the loose LTE case.

The difference between the required fixed sensor density for the strict and loose LTE case is very large, which is partly due to the very different maximum interference probability requirements (10^{-6} versus 10^{-3}). These requirements can be specified by the regulator or the cognitive operator can make an agreement on this depending on the situation. Since the probability of interference requirements probably will be set in an agreement between the owners of the joint venture, it should be expected that these requirements will be somewhat lower in this case than when the regulator specifies the requirements. Hence the required number of fixed sensors is expected to be somewhere between the maximum values shown in Figure 2 and Figure 3 (i.e. 120 and 10.5 sensors/km^2). We will use 65 sensors/km^2 in this business case, which represents the mean of the values for the strict LTE and loose LTE cases[1].

2) Fixed sensor network roll-out

It is assumed that the fixed sensor network will be rolled out in three stages. In the first stage taking place in 2015, it will be rolled out in the downtown area. Then the fixed sensors will be deployed in the suburban areas of the city in two stages, the first in 2016 and the second in 2017.

3) Fixed Sensor Price

The complexity of a fixed sensor was estimated to be about the same as that of a Wi-Fi Access Point. In addition it must be taken into account that these sensors will be placed outdoors and must stand different types of weather conditions. With these inputs a natural assumption is that the price of a fixed sensor will be about the same as the price of an outdoor Wi-Fi Access Point. This price is typical several hundred Euro today. Taking into account technical development and price reduction expected from now until 2015, we will assume that the price of a fixed sensor is 300€ in 2015 decreasing to 177.1€ in 2020.

4) Fixed Sensor Installation Costs

The fixed sensor installation costs include truck roll, mounting the sensor, connect it to the mains and provide a wired or wireless connection. All fixed sensors in an area should be mounted at the same time to minimize the truck roll expenses. We will assume that one man will mount a sensor in 1 hour on average including the time it takes to drive between the sensor sites, and that the hourly costs for him and the van is 50€ in 2015 decreasing to 45.2€ in 2020.

5) Fixed sensor operational costs

The fixed sensor operational costs cover sensor site rental, power consumption and maintenance.

It is important that the fixed sensors are robust with a very high mean time between failures. Most of the reconfiguration and adjustment of the sensors should be controlled through its wired or wireless sensor network connection. If a maintenance visit is required once every 3 years (36 months) on average and the cost of a maintenance visit is 50€, the average monthly costs would be 1.4€/month/sensor.

We assume that a fixed sensor consumes 10W at average, giving a monthly electricity consumption of 7.2kWh. With a tariff of 0.30€/kWh, the monthly electricity costs is about 2.2€/sensor/month.

The average fixed sensor site rental cost is more difficult to estimate. The sensors will be relatively small of size similar to an outdoor Wi-Fi access point. They will typically be placed where there is an easy access to the mains, for example at top of lamp posts. We estimate the average sensor site rental to be in the order of 10€/month/sensor. Based on these considerations we assume that the total fixed sensor operational costs is 15 €/month/sensor in 2015 decreasing to 13.6€ in 2020.

6) Fusion centre costs

The fusion centre costs consist of the purchasing, installation and operational costs. We assume that one fusion centre is sufficient and that this is located at the joint ventures office so that the place rental, electricity costs and maintenance are included in the company's general operating costs. The fusion centre will consist of a powerful computer with high communication capacity. We will assume that the price for the fusion centre is 150,000 € and installation costs are 10,000 €.

7) Subsidization of user terminals

Having sensing capabilities in the terminals can reduce the need for fixed sensors. Hence, it can be a good idea for a SENDORA operator to subsidize user terminals with sensing capability to reduce costs for the fixed sensor network. However, we will not consider such subsidies in the business case calculations.

D. Cognitive radio access related assumptions

The CR access related assumptions consists of the costs for installing and operating the CR BSs and for establishing new BSs sites.

[1] Further details on the LTE study can be found in the coming deliverable D6.3 in the SENDORA project at http://www.sendora.eu.

1) Number of cognitive base stations

The geographical density of BSs for the SENDORA systems is assumed to be similar to that for mobile broadband networks. Hence, a SENDORA operator that can exploit BSs sites of a mobile broadband operator as in the joint venture case can often get the required coverage and capacity without having to establish any new BS sites.

The number of cognitive BSs required in the targeted city is assumed to increase from 50 the first year to 450 after 5 years. These numbers are based on operator experience from deploying 3G cellular networks.

TABLE 5 NUMBER OF COGNITIVE BSS DEPLOYED AT THE END OF EACH YEAR

Year	2015	2016	2017	2018	2019	2020
#Cognitive BSs	50	175	250	350	400	450

As the base case it is assumed that the operator will get sufficient capacity and coverage by sharing infrastructure with the operators behind the joint venture, such that it is not necessary to establish new BS sites. Establishment of new BS sites will however be considered in the sensitivity analysis.

2) Costs for installation of cognitive functionality in BSs

It is assumed that at least one of the owners of the joint venture is a cellular operator having an infrastructure of BSs and backhaul in the area. The joint venture operator can outsource cognitive BS functionality to the cellular operators. The cellular operators can update their BSs, which by 2015 is based on software defined radio solutions. It is assumed that the costs for updating/upgrading a BS with cognitive functionalities is 5,000€ in 2015 decreasing to 2,953€ in 2020.

3) Cost for establishing new sites

If updating/upgrading existing BS with cognitive functionality does not give the required coverage and capacity, it will be necessary for the SENDORA operator to establish new sites. The cost for establishing a site consists of costs for identifying and acquiring the site, building the antennas, housing and providing it with power and backhaul.

It will be assumed that the costs for establishing a new SENDORA BS site is comparable to that of establishing a new 3G cellular BS site. Based on operators' experience we will estimate this cost to be 60,000€. In the base case it is assumed that no new sites are required.

4) Costs for cognitive base station maintenance, backhaul rental and site rental

The costs associated with renting the BS site, renting backhaul capacity and maintaining the BS is assumed to be 1,000€/month/site in 2015, decreasing to 904€/month/site in 2020.

5) General OPEX

This OPEX reflects the general efficiency of the joint venture and covers e.g. customer acquisition (sales and marketing) costs and general operation of the company. Its value is highly uncertain and difficult to benchmark due to different accounting principles in different companies and countries. It is mostly independent of the SENDORA concept. The value used for general OPEX is 8€/subscriber/month in 2015 decreasing to 5.6€ in 2020.

VI. BUSINESS CASE 1: SPECTRUM SHARING

The main idea behind this business case illustrated in Figure 4 is that several spectrum owners establish a joint venture and this joint venture gets the rights to use the "unused" spectrum resources of all those spectrum owners in a cognitive way based on the SENDORA concept.

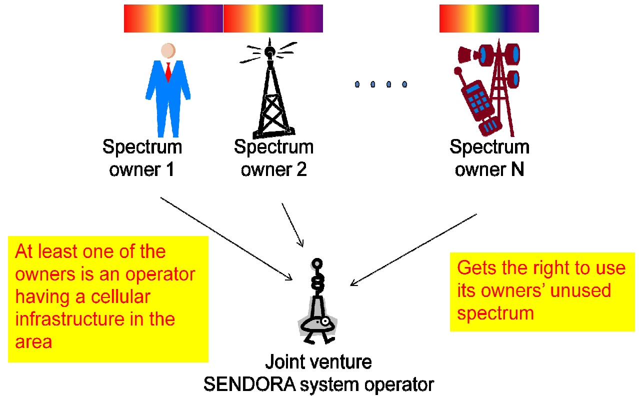


Figure 4. A number of spectrum owners form a joint venture operator that gets the rights to use the "unused" spectrum resources of all those spectrum owners in a cognitive way based on the SENDORA concept

The joint venture will build a fixed sensor network and will provide a cognitive nomadic broadband service in the "unused" spectrum. The business case is calculated from the point of view of this joint venture where the mother companies establish the joint venture and hope to get the invested money back by receiving dividends from the joint venture. The success criterion could be for example that the pay-back period (time until accumulated cash flow turns positive) is less than five years.

The spectrum owners can be of different types, for example companies having bought spectrum just as an investment, cellular operators and broadcast operators. However, it is assumed that at least one of the spectrum owners is a cellular operator having an infrastructure, including backhaul and BS, in the area. Then the joint venture can reuse this infrastructure by leasing CR access functionality and backhaul capacity from the cellular operator.

Due to the close connection between the joint venture and the owners of the spectrum used, it can be expected that the maximum levels of interference accepted by the spectrum owners can be somewhat relaxed compared to the case where the spectrum owners do not get any economical benefits for the secondary use of their spectrum.

The joint venture represents a practical way of dividing the incomes and expenses of the CR network between the spectrum owners. The composition of the joint venture is very important and should ensure both that the CR network get access to sufficient spectrum resources and that there are little need to build new infrastructure (e.g. BS sites).

From a strategic point of view spectrum sharing is not much used today. However, it can be seen as a natural extension of infrastructure sharing, which used to be limited to sharing of non-electronic infrastructure (e.g. antenna mast) but has now been extended to sharing of electronic infrastructure. Sharing important network elements like BSs was almost unthinkable from a strategic point of view only a few years ago but is now becoming increasingly popular.

From a regulatory point of view, this business case is probably one of the easiest to implement since the joint venture operator uses only the owning companies' spectrum. Hence, the main regulation of acceptable interference can be done among the joint venture owners and little coordination is required with external spectrum owners. If technology neutral regulations applies to for the frequencies used by the joint venture operator, there should be no or little need for coordination and for getting permissions from the regulator.

A. Base case

The business case calculation was first done with the assumptions given and explained in the previous sections. By combining costs (CAPEX and OPEX) with revenues the yearly cash flows and standard profitability indicators, like NPV, IRR and pay-back period, was calculated. For the definition of these, please refer to section IV.

It is important to emphasize that SENDORA is an innovative concept and much research remains before it becomes a mature technology. This means that many basic assumptions in the business case calculations will remain uncertain for a long time. Hence, the results will not give definite answers but only indications to whether it is possible to make business utilizing the SENDORA concept.

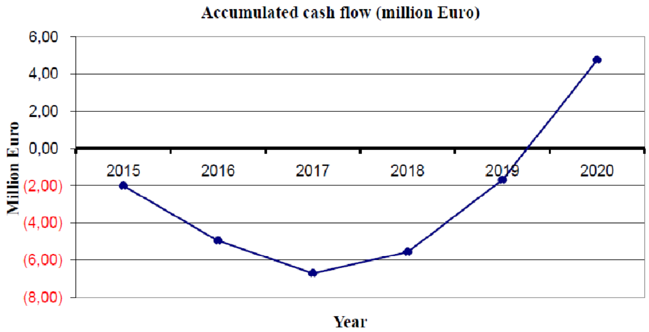


Figure 5. Accumulated cash flow for the "Spectrum Sharing" business case.

Figure 5 shows the accumulated cash flow for the study period 2015 – 2020 with the assumptions given in the previous sections. NPV for the study period 2015-2020 is 1,36 million Euro, IRR is 16 % and the pay-pack period is about 5 years.

The accumulated cash flow and the associated economical results are quite similar to many others telecommunication infrastructure projects. That means that it will be tough and a long-term business case, where the operator (joint venture) must be patient and have financial strength with long term financing to wait a longer period for the return on investment.

B. Sensitivity analysis

As already underlined, the input assumptions for this kind of future oriented business case are uncertain. Therefore it is interesting to see how changes of the value of different parameters affect the results.

There are many aspects, which are independent of the SENDORA concept, but have crucial influence on the profitability. Examples of these are the operational efficiency of the joint venture (influencing OPEX) and the competition situations (influencing ARPU and number of customers). We do not evaluate these aspects further, except doing sensitivity analysis on ARPU, but concentrate on aspects where the SENDORA concept has crucial influence.

Sensitivity analysis is done here by changing the value of one critical input parameter and showing how the economical results are changing. All other input parameters are as in the "Base case". NPV is used as the indicator of profitability.

1) Fixed sensor density

Since the novel idea in SENDORA is to combine CR with sensor networks, the required number of fixed sensor per km^2 is one of the most crucial parameters for the SENDORA approach. Also, as explained in Section V.C, there are large uncertainties associated with this number. For example is it uncertain what probability of interference the spectrum owners will accept.

TABLE 6 NPV SENSITIVITY FOR CHANGES TO THE FIXED SENSOR DENSITY

# fixed sensors per km^2	NPV [MEuro]
10	11.44
30	7.77
65	**1.36**
72	0
120	-8.72

Table 6 lists NPV for different values of the fixed sensor density. As can be seen, the business case is very sensitive to changes in this parameter. Just by increasing the sensor density from 65 to 72 sensors/km^2, which is a very small change from a technical perspective, the NPV starts getting negative.

In section V.C the fixed sensor density for two cases, strict LTE and loose LTE, were presented. The required sensor densities ranged from 10.5 sensors/km^2 in the loose LTE case to 120 sensors/km^2 in the strict LTE case. Clearly, these values give extremely different results for the business case.

The fixed sensor density requirement can for example be reduced by employing more advanced sensing techniques or complementing sensing data with other information (e.g. from the primary operators). Also, this analysis shows that it is important that regulators and spectrum owners have this in mind when deciding on the interference probability limits.

2) Fixed sensor price

Sensitivity analysis of the fixed sensor price is interesting since it concerns the sensor network, which is central to the SENDORA concept. The price for a fixed sensor is uncertain since such equipment has not been produced yet, but is still researched on and exists as prototypes at best. The price used in the base case was derived by comparing it to outdoor Wi-Fi access points, which is expected to have similar complexity and enclosure requirements.

TABLE 7 NPV SENSITIVITY FOR CHANGES TO FIXED SENSOR PRICE

Fixed sensor price [Euro]	NPV [MEuro]
50	3.98
150	2.93
300	**1.36**
430	0
500	-0.74
700	-2.84
1000	-5.99

Table 7 lists the NPV for different values of the fixed sensor price. It can be seen that the fixed sensor price must be raised from 300€ to 430€ (43%) before the NPV gets negative. A similar moderate change in the NPV can be seen if the price is halved from the base case value.

It can be concluded that the fixed sensor price is not the most sensitive parameter, but still important. It will be a challenge to meet the cost assumptions used in the base case, but moderate deviations (say ±10%) from this is not critical for the business case.

3) Fixed sensor OPEX

The operating cost of fixed sensors (electricity, maintenance, sensor site rental) is a very uncertain parameter, especially the sensor site rental component. It is important to determine the sensitivity of the business case for this parameter to assess the importance of fixed sensor power consumption, durability and space requirements.

TABLE 8 NPV SENSITIVITY FOR CHANGES TO THE FIXED SENSOR OPEX

Fixed sensor OPEX [€/month/sensor]	NPV [MEuro]
5.0	6.82
10.0	4.09
15.0	**1.36**
17.5	0
20.0	-1.37
25.0	-4.10

Table 8 lists NPV for different values of the fixed sensor OPEX. It can be seen that if the OPEX is increased from 15 to 17.5€/month/sensor, the NPV starts getting negative. This is a small increase (16%); much smaller than the uncertainty of this parameter. Hence, this is a parameter that a CR operator must have under control before deciding to build such a network.

The high sensitivity for this parameter shows that it is critical that the fixed sensor power consumption is low and that the mean time between failures is long. The first requirement can be achieved by exploiting the appropriate integrated circuit technologies, while the second requirement can be met by ensuring that the sensors have high quality and integrate "self-healing" capabilities in the units.

4) Share of new sites

In this business case it is assumed that at least one of the spectrum owners owning the joint venture is a cellular operator, and that the joint venture operator can exploit the existing infrastructure (e.g. sites, BSs and backhaul). However, it might turn out that it is necessary to establish some new sites in addition to the existing ones in order to get the wanted coverage and capacity.

In the base case it is assumed that no new sites are built. In a real situation this assumption might turn out to be optimistic, and it is hence interesting to see how the business case is affected if different shares of the sites are new sites.

Table 9 lists the NPV for different shares of new sites. It can be seen that the NPV starts getting negative if the share of new sites exceeds 6%. If a large part of the sites are new sites, the business case will be strongly negative. Hence, it is important that new sites are avoided. However, if the share of new sites can be limited to a few percent, the business case will be only moderately affected.

TABLE 9 NPV SENSITIVITY FOR CHANGES TO THE SHARE OF NEW SITES

Share of new sites	NPV [million Euro]
0 %	**1.36**
6 %	0.00
10 %	-0.89
20 %	-3.03
30 %	-5.28
40 %	-7.43
50 %	-9,67

5) Subscription fee

An important parameter for the business case is the subscription fee, also called the ARPU. This is a parameter that depends mostly on what price level that is formed in the market for wireless broadband services, and is therefore not directly related to the SENDORA concept. However, the ARPU depends on how the customers grade the service provided by the SENDORA network. If the joint venture operator is able to provide a service which is better than assumed here, the ARPU will be higher than assumed in the base case. If the grade of the service provided is lower than assumed, the ARPU will be lower than in the base case.

TABLE 10 NPV SENSITIVITY FOR CHANGES TO THE ARPU

ARPU [€/month]	NPV [MEuro]
15.0	-9.33
18.0	-2.92
19.4	0
20.0	**1.36**
25.0	12.04

Table 10 lists the NPV for different ARPUs. It can be seen that the ARPU is a very critical parameter for the business case. The NPV starts getting negative after a reduction of the ARPU with only 3%. Larger changes of the ARPU give dramatic changes of the NPV.

The ARPU assumption used in the base case was based on a comparison with current mobile broadband subscription fees. Since it is uncertain how much lower the subscription fee for a SENDORA service will be, this assumption is much more than a few percent uncertain. This results shows that it is of crucial importance to be able to offer a service that is preferably better, or at least not much worse, than that of mobile broadband services with respect to average and peak capacity, coverage, delay, QoS, etc.

VII. BUSINESS CASE 2: SPECTRUM BROKER

This business case will be calculated from the point of view of a spectrum broker. The spectrum broker is an entity that deploys (builds and operates) a sensor network and sells either sensing information or information on spectrum usage opportunities to one or more CR operators. It is assumed that the spectrum broker is only charging money to cover its expenses, that is it is assumed that its revenues should be such that the broker will have NPV = 0 for the study period 2015-2020 for building and operating the fixed sensor network. This non-profit broker could be the regulator or an entity set up by the government or local authorities.

This business case scenario is more challenging than the previous business case from a regulatory point of view. CR operation must be allowed in the spectrum used and there must be sufficient amounts of such spectrum available to allow a small number of CR operators to offer an attractive service with these spectrum resources. The regulatory process for opening frequency bands for cognitive operation can be complex and take long time, where multiple stake holders are consulted and detailed rules governing the CR operation have to be developed.

It is assumed that the spectrum broker or the CR operators will not pay anything to the owners of the spectrum. Since the spectrum owners are not part of this specific SENDORA ecosystem and they will not get any compensation when others are using their spectrum, it is fair to assume that they should not experience any noticeable interference from the cognitive operation. Therefore it is reasonable to assume that there will be stringent requirements for the interference generated into the primary systems. Taking into account the results on the required fixed sensor density presented in section V.C, we will use the strict LTE case as the basis for the assumptions made. Hence, it will be assumed that the spectrum broker must deploy 120 sensors/km^2 both in the downtown area and the suburban area of the city.

The marginal (additional) OPEX for the broker to handle the relations to the cognitive operators is set to 200,000 €/year.

All other assumptions regarding sensor network establishment and operation are the same as in the first business case. The broker is not a cognitive operator, so all items related to cognitive operation is not included to this case.

This business case will only give one results, and that is how much the broker must charge from the CR operators in order to have NPV=0 for the study period 2015-2020. This number will be an important input to the next business case, which considers a new CR operator that will use information of vacant spectrum from the broker.

Since it takes some time for the broker to build the fixed sensor network, the service it can provide to the CR operators will be reduced in the start. To take this into account we assume that the broker will only charge half of the yearly fee the first year.

The business case calculations shows that the fees the broker must charge from the CR operators using his information are 2,693,000€ in 2015 and 5,386,000€ for each of the remaining years.

VIII. BUSINESS CASE 3: NEW ENTRANT

This business case takes the perspective of a new CR operator that does not have any existing infrastructure or frequency licenses in the area in question. The operator wants to use a SENDORA system to offer a nomadic mobile broadband service.

The new entrant will build a CR access network, both by sharing infrastructure with existing wireless operators in the area and by building new BS sites. The spectrum needed will be borrowed or rented from the spectrum broker addressed in Section VII. It is assumed that the spectrum broker has deployed a sensor network and all related infrastructure, so the operator does not have to deploy a sensor network itself. However, the cognitive terminals will have sensing capability that the operator might use to improve the quality and resolution of the information received from the broker.

The business case of a new SENDORA operator is somewhat similar to a corresponding business case of a new mobile broadband operator, e.g. a new LTE operator. The difference is that a new mobile broadband operator has to acquire a spectrum license, while the SENDORA operator will base its operation on borrowed or rented spectrum.

All revenue assumptions (number of customers and ARPU) for this business case are the same as for the spectrum sharing business case presented in section VI. The main difference is that the new entrant will not have to build and operate a sensor network as the joint venture operator does, but it can utilize the sensor network information either for free (base case for new entrant) or by paying to the broker an annual fee (section VII). When building and operating the cognitive network we assume that the new entrant in some aspects will have higher costs than the joint venture:

- The SENDORA operator has to establish new BS sites for 20% of the BSs needed (the total number of BSs is the same as in the joint venture case, see Table 5). It is assumed that it costs 60,000 € to establish a new site.
- For the cognitive functionalities in the BSs 10,000 € (decreasing to 5,905 € in 2020) is assumed for equipping it with the needed CR BS components (antennas, modems, amplifiers, etc.). In the joint venture case a lower value (5,000€) is used.
- The new CR operator has to pay a 50% higher rent for sharing infrastructure with the existing operators in the area than in the spectrum sharing business case from section VI. It is assumed that the new entrant must pay a rent to other operators for sharing the BS site, maintenance expenses and backhaul sharing of 1,500 €/month/BS site decreasing to 1,356 € in 2020.

As the base case we will assume that the new entrant do not have to pay anything for the spectrum. This means that the broker must cover the costs of building and operating the sensor network, i.e. this has then to be financed by public money. The base case will however be complemented with a sensitivity analysis to assess how the business case is affected if the operator has to pay for using the spectrum. In this case the price that the new cognitive operator has to pay for the spectrum will be derived from the revenue the broker, presented in the business case in section VII, must have in order to get NPV=0 in the study period 2015-2020. This cost might be shared with other CR operators in the area also using sensing information from the broker.

Figure 6 shows accumulated cash flow for the base case. NPV for the study period 2015-2020 is 0.61 million Euro, IRR is 14 % and the pay-pack period is somewhat less than 5 years. This case is even more uncertain than the spectrum sharing case (section VI) and it is quite impossible to state on a general level how profitable a new entrant could be. It depends on local conditions, efficiency of the new entrant, competition situation, timing, regulatory conditions etc. It is important to note that in this base case the new entrant do not have any spectrum costs, which may be an unrealistic assumption even on a longer term.

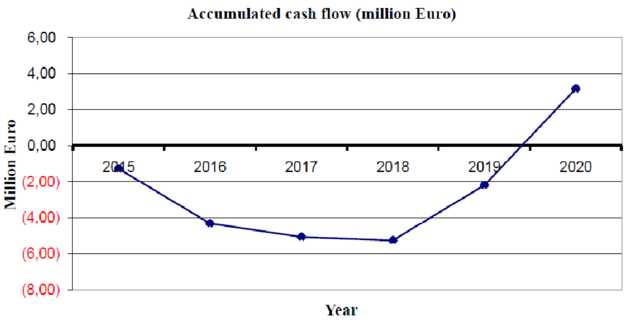


Figure 6 Accumulated cash flow for the base case

A sensitivity analysis was performed for the number of new BS sites and for having to pay for the spectrum. Table 11 lists the NPV for different shares of new BS sites.

TABLE 11 NPV SENSITIVITY FOR CHANGES TO THE SHARE OF NEW BS SITES

Share of new BS sites	NPV [million Euro]
0 %	5,00
20 %	**0,61**
22 %	0
40 %	-3,78
100 %	-16,96

The table shows that the NPV starts getting negative when the share of new sites is increased from 20% to 22%. The uncertainty of how many new sites that is required is typically much larger than this. Hence, this is a parameter that a new entrant must have good control of. If the share of new sites can be reduced below the 20% assumed in the base case, it will affect the business case very positively.

TABLE 12 NPV WHEN A NEW ENTRANT HAS TO PAY FOR THE SPECTRUM FOR DIFFERENT NUMBERS OF COGNITIVE RADIO OPERATORS IN THE AREA

# CR operators in the area	NPV [MEuro]
1	-22,50
2	-10,95
3	-7,09
4	-5,17

Table 12 lists NPV when the new entrant has to pay for the spectrum for different numbers of CR operators in the area (when number of operators is 1, the new entrant is the only cognitive operator in the area). It can be seen that the business case is negative if the new entrant has to pay the broker for spectrum information, even if the broker's costs are divided between 4 cognitive operators in the area. Taking into account the market share that has been assumed (100,000 subscribers in 2020 of a population of 1 million), it is even unrealistic to assume that there will be room for four CR operators. Two or three operators are probably the most realistic numbers.

IX. CONCLUSIONS

This paper proposed and evaluated three business case scenarios for deployment of a sensor network aided cognitive radio system studied in a typical European city; a spectrum sharing, a spectrum broker and a new entrant business case scenario. Traditional cash flow analysis was used to get an indication of profitability and sensitivity analysis was used to identify critical parameters of the system due to large uncertainties in the input parameters.

It should be noted in the conclusions that the main value of these business case calculations is the identification of critical aspects for profitability of a sensor network aided CR system, so that future technical R&D work can focus on them. The most critical aspects influencing the profitability were required fixed sensor density and fixed sensor OPEX, where the former depends strongly on what interference limits are set to protect the primary operators. By using different, but all realistic, values for interference limits, it was shown that the required density of fixed sensors could vary by a factor of 10 or more, which indicates that it is important that regulators and spectrum owners consider this when deciding on interference probability limits. The high sensitivity for the fixed sensor OPEX showed that it is critical that the fixed sensor power consumption is low and that the mean time between failures is long.

The spectrum sharing business case is probably one of the best possible cases for the studied system because the joint venture operator has free access to frequency resources of the mother companies, detailed knowledge of the primary systems and good possibilities for sharing infrastructure with the operators owning the spectrum. The new entrant business case scenario is most challenging to make viable, if the new entrant has to pay the broker what he needs for covering his expenses, the business case gets strongly negative even when these expenses are shared with three other cognitive operators also using information from the broker.

ACKNOWLEDGMENT

The research leading to these results was performed in the project SENDORA which receives funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 216076. The authors want to thank the other participants in the SENDORA project for providing necessary input data and for giving us valuable feedback during the work.

REFERENCES

[1] V.Fodor, R.Thobaben, B.Mercier et al, "Sensor Networks for Cognitive Radio: Theory and System Design", ICT Mobile Summit, June 2008.

[2] Grondalen, O.; Lahteenoja, M.; Gronsund, P.; , "Business case proposal for a cognitive radio network based on Wireless Sensor Network," *CROWNCOM, 2010*, pp.1-5, 9-11 June 2010

[3] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum," in World of Wireless Mobile and Multimedia Networks. WoWMoM, June 2005, pp. 78–85.

[4] V. Brik, E. Rozner, S. Banerjee, and P. Bahl, "Dsap: a protocol for coordinated spectrum access," in New Frontiers in Dynamic Spectrum Access Networks. DySPAN, Nov. 2005, pp. 611–614.

[5] Pieter Ballon, (2007) "Business modelling revisited: the configuration of control and value", info, Vol. 9 Iss: 5, pp.6 - 19

[6] Chapin, J.M.; Lehr, W.H.; , "Cognitive Radios for Dymanic Spectrum Access - The Path to Market Success for Dynamic Spectrum Access Technology," *Communications Magazine, IEEE* , vol.45, no.5, pp.96-103, May 2007

[7] FCC, *"Second memorandum opinion and order,"* Tech. Rep. ET Docket No. 10-174, Sept. 2010.

[8] http://www.investopedia.com/dictionary/

[9] Richards, F.J. 1959 A flexible growth function for empirical use. J. Exp. Bot. 10: 290—300

[10] Viktoria Fodor, Ioannis Glaropoulos and Loreto Pescosolido, "Detecting low-power primary signals via distributed sensing to support opportunistic spectrum access," IEEE ICC 2009, vol. 32, no. 1, June 2009, pp. 2929-2934

Paper C
Comparison of Cell Sizes for Cost Efficient Deployment of a Sensor Network Aided Cognitive Radio System

Pål Grønsund and Ole Grøndalen

Journal of Signal Processing Systems, vol. 69, no. 1, pp. 95-104, Oct. 2012.

Springer Journal of Signal Processing Systems manuscript No.
(will be inserted by the editor)

Comparison of Cell Sizes for Cost Efficient Deployment of a Sensor Network Aided Cognitive Radio System

Pål R. Grønsund · Ole Grøndalen

The final publication is available at http://dx.doi.org/10.1007/s11265-011-0636-4

Abstract To exploit spectrum resources on a secondary basis, a Sensor Network Aided Cognitive Radio Network uses a wireless sensor network that assists a secondary cognitive radio network by providing information about the current primary spectrum occupancy. In this paper we determine the performance for different cell sizes when considering the costs for deployment of base stations in a secondary network that exploits spectrum holes identified by the wireless sensor network. The secondary base station is deployed co-located with a mobile primary network that uses a cellular reuse pattern with seven frequencies. Performance of the secondary system and impact on the primary system are mainly studied in terms of throughput, packet loss and coverage when using spectrum holes in the space, time and frequency domains. Especially, we find that the cell size and configured transmit powers for the secondary system are important for optimal system performance, and that smaller cell sizes and less expensive base stations for the secondary system are beneficial. The impact on primary system performance was found to be low, but that optimal tuning of the sensor network is important.

Keywords Cognitive Radio · Sensor Network · Cell Size · Dynamic Spectrum Access · Throughput

P. R. Grønsund (Corresponding Author)
Telenor, Snarøyveien 30, 1331 Fornebu, Norway
E-mail: pal.gronsund@telenor.com

O. Grøndalen
E-mail: ole.grondalen@telenor.com

1 Introduction

Cognitive radio (CR) and spectrum sensing are considered as promising concepts to exploit the spectrum resources more efficiently by dynamically utilizing radio spectrum not utilized by primary networks, referred to as spectrum holes. A wireless sensor network (WSN), not necessarily embedded in the CR, can be deployed to detect spectrum holes and report to the secondary system as proposed in the EU FP7 project SENDORA [1,17]. In this paper we will refer to the SENDORA system as a Sensor Network Aided Cognitive Radio system where the secondary CR system uses a WSN to detect spectrum holes. Input on real time spectrum monitoring by using a separate low cost WSN was recently also requested by FCC [8].

In [13], we studied the system level performance of an example SENDORA system for different secondary cell sizes. A total performance study of the SENDORA system is complex to achieve with analytical modelling, hence the system level simulator ns-2 was used. In this paper we build on that work and present an elaborative and complete study. All parts of the SENDORA system are implemented in the simulator; a primary network, a centralized secondary network, a WSN and a centralized fusion centre (FC). The FC aggregates spectrum measurements from the sensors and allocates a channel to the secondary network. Furthermore, to get a detailed picture of performance we implement realistic network topologies, traffic models and the whole protocol stack of the secondary and primary systems with actual transport, network, link and physical layers.

In [11] we found that a high degree of co-location of secondary and primary base stations (BSs) is very important in order to achieve a positive business case for a SENDORA system. For the study in [11], it was found that more than 6% increase in number of non co-located cells would lead to a negative business case. Therefore the main focus of this study is to determine the performance for different cell sizes and transmit power levels when considering the costs for deployment of the secondary network when co-located with a primary network. A realistic network scenario is considered where the primary network uses a cellular reuse pattern with seven frequencies.

Achievable rate for point-to-point communication using a potential spectrum hole in a frequency planned primary network was studied in [5] by using monte-carlo simulations. It was found that spectrum holes get saturated quite fast due to interference among cognitive users. Similar studies were performed in [14] for a single cell and in [16] for a frequency planned network. These works assumed a reduction in primary cell size as a compromise for the primary system to allow secondary users (SUs) and that the SUs can perfectly judge the distance to the primary users (PUs). In this paper, we consider a point-to-multipoint network, a realistic channel model and that PUs are mobile such that the considered spectrum holes [18] change dynamically in time and space. An interference requirement to allow secondary operation uses a constraint on interference at the PU [9, 10, 19], estimated by the FC by querying the WSN for presence of PUs.

The main focus and contribution of this paper is on determining realistic network performance for different cell sizes when considering costs for deployment in a SENDORA system by simulations, and on how spectrum holes can be exploited while respecting primary system interference constraints. Impact on the primary system performance will also be studied. It should also be noted that the objective of this paper is not on optimization of algorithms.

The organization of the rest of this paper is as follows: Section 2 gives an overview of the SENDORA system. The network scenario considered is described and the necessary parameters and constraints are derived in Section 3. In section 4, we present and motivate the simulation scenarios that will be studied in detail. An analytical estimation of service range and coverage is given in Section 5 before the simulation results and performance evaluation are presented in Section 6. Finally, the paper is concluded in Section 7.

2 Sensor Network Aided Cognitive Radio System

Fig. 1 gives an overview of the SENDORA system consisting of four main parts; the primary network which in this case is WiMAX, the secondary network which in this case is a modified version of WiMAX with SENDORA functions implemented, the WSN and the centralized FC.

To get a channel allocation, the secondary network consults the FC which has the total responsibility for communicating with the WSN. The FC then allocates an available channel to the secondary system based on sensing results. The simulation model for the primary and secondary networks uses an ns-2 implementation of WiMAX [2] developed in WiMAX Forum. The FC and WSN are also implemented in ns-2. Each part of the SENDORA system will be described in the sequel of this section.

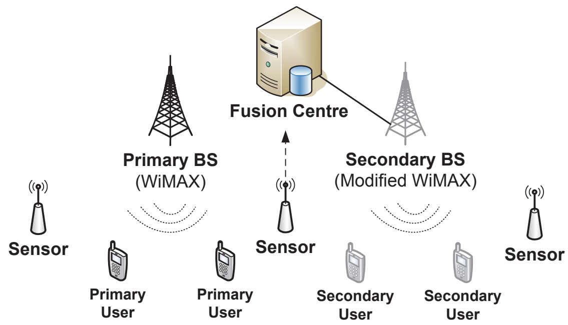


Fig. 1 System Model

2.1 Primary System

To simulate the primary system, we use the WiMAX ns-2 model developed in WiMAX Forum which is based on the IEEE 802.16e [3] standard. The model includes a very detailed model of the MAC and also a good model of the PHY layers. The main parameters given in Table 1 are common for the primary and secondary systems. WiMAX uses orthogonal frequency division multiple access (OFDMA) and time division duplex (TDD) with 5 milliseconds OFDMA frames. Operating frequency is in the 2 GHz band and the channel bandwidth is 10 MHz with a total of 1024 subcarriers.

2.2 Wireless Sensor Network

The WSN is deployed in a rectangular grid and provides information about spectrum occupancy in the area where the secondary network is deployed. Each sensor senses all the primary frequency bands. Furthermore, the sensors are energy detectors. Therefore the WSN needs to synchronize quiet periods with the secondary system, which are time periods of a certain length with certain intervals in between when the secondary system stops

Table 1 Parameters for both primary and secondary systems

Parameter	Value
Frequency	2 GHz
Channel bandwidth	10 MHz
FFT size	1024
Duplexing method	TDD
OFDMA Frame size	5 ms
DL:UL ratio	2:1
Modulation types	BPSK, QPSK, {16,64}-QAM
FEC rates	1/2, 2/3, 3/4
Cyclic prefix mode	1/4
OFDM mapping	Vertical striping
Total subcarriers used	840
Guard & null subcarriers	184
Pilot subcarriers	DL: 120, UL: 280
Data subcarriers	DL: 720, UL: 560
Subcarrriers/subchannel	DL: 24, UL: 28
Subchannels	DL: 30, UL: 35
OFDMA symbols/frame	48
Subcarrier allocation	Partially Used Subcar. Alloc.
Sensing	Energy detection
Sensing period	30 ms
Sensing interval	0.5 second

transmitting and the sensors senses primary activity. The WSN communicates its sensing result to the FC responsible for allocating frequencies to the secondary system.

Since the primary mobile WiMAX network is a slotted system with periodic MAC frames of 5 milliseconds where signals are transmitted irrespective of PU activity due to management traffic, the WSN uses real-time local sensing outcomes generated for each OFDMA frame during the sensing period. After the sensing period, the maximum received signal strength from these sensing results is reported to the FC. Sensing periods of 30 milliseconds are scheduled at specific time intervals each 0.5th second. Each sensor measures activity on all potential channels for use by the secondary system. A common control channel is used for reporting sensing measurements.

2.3 Fusion Centre

The FC collects information from the sensors and will at any time have a near real-time overview of the spectrum occupancy for the area covered by the WSN. Upon spectrum request from the secondary system, the FC uses an algorithm that consults a matrix containing spectrum usage measurements for all potential channels from all sensors in order to allocate available channels to the secondary system. Each matrix element represents a sensor in the WSN. Required functions for receiving sensor reports, calculating the spectrum map, managing allocations and communicating with the secondary system are implemented in the FC. The channel allocation algorithm allocates one of the available channels not used by the primary system.

2.4 Secondary System

The secondary system is also based on WiMAX and the ns-2 simulator model developed in WiMAX Forum. The simulator model is modified with new functionality required to operate as a secondary cognitive radio system. A centralized secondary network that consists of a secondary BS and a set of SUs is considered. The secondary system communicates with the FC in order to obtain a vacant channel for communication.

Two main cognitive functions are implemented in the secondary system. The first is a cognitive actuation module that communicates with the FC to obtain an available frequency allocation and thereafter actuates this in the secondary system. The second is time synchronization with the WSN for quiet periods during which the WSN can measure primary activity.

For the cognitive actuation module, the secondary BS communicates with the FC to obtain an available frequency for its coverage area and informs the SUs about the operating frequency. The BS is not aware of the SU coverage area and therefore the SU also queries the FC to check if the allocated frequency is available for it. If the frequency is not available for one of the SUs, the affected SU notifies the BS which queries the FC for a new frequency.

3 Network Model

The considered network scenario is illustrated in Fig. 2, where the primary network uses hexagonal cells without sectorization. There are totally 7 frequencies from $F1$ to $F7$, in the 2 GHz band. The primary network operator uses totally 70 MHz, 7 bands of 10 MHz. The secondary system consists of one BS cell co-located with one of the primary BSs illustrated by the BS with two antennas in Fig. 2. The secondary BS and its SUs will use one of the frequencies $F2$-$F7$ if available, where $F1$ not will be used because the primary BS and PUs of that cell will be within interference range. Both primary and secondary BS and subscriber station heights are set to 30 and 1.5 meters respectively. The distance between primary BSs is 2 km and with hexagonal shaped cells the radius is 1.15 km. It is assumed that the primary system is noise limited. There are 65 sensors/km^2 [11]. In the remainder of this section we estimate simulation parameters to be used for this scenario.

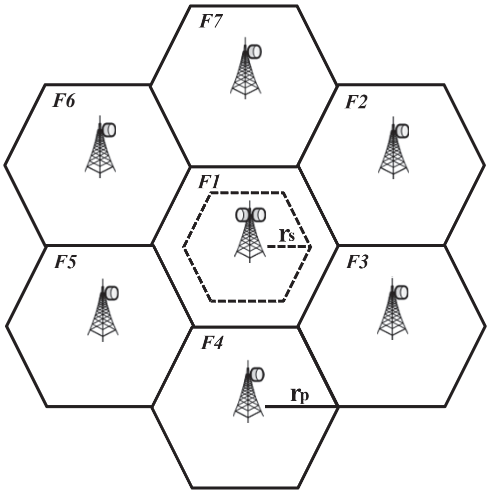


Fig. 2 Network Design

3.1 Path Loss and Channel Model

The COST Hata model [7] is valid for distances above 1 km and the Cost Walfish-Ikegami (WI) [7] for distances above 20 m. Both models are valid for the 2 GHz frequency band. We use a path loss model which agrees with the COST-WI line-of-sight model for short distances d and with the COST Hata model at distance above 1 km:

$$a = \mathrm{P}_\mathrm{L}^\mathrm{WI}(1km), \qquad (1)$$
$$b = \mathrm{P}_\mathrm{L}^\mathrm{Hata}(1km),$$

$$\mathrm{P}_\mathrm{L} = \begin{cases} \mathrm{P}_\mathrm{L}^\mathrm{WI} + d(b-a), & d < 1km, \\ \mathrm{P}_\mathrm{L}^\mathrm{Hata}, & d \geq 1km \end{cases} \qquad (2)$$

The COST Hata model is defined as:

$$\mathrm{P}_\mathrm{L}^\mathrm{Hata}(d) = 46.3 + 33.9\log_{10}(f_\mathrm{c}) - 13.82\log_{10}(h_\mathrm{t}) \qquad (3)$$
$$- a(h_\mathrm{r}) + (44.9 - 6.55\log_{10}(h_\mathrm{t}))\log_{10}(d) + C_\mathrm{M},$$

where d is the distance in kilometers, f_c is the center frequency in MHz, h_t and h_r are BS and subscriber station height in meters respectively, C_M is a correction factor dependent on surrounding areas (3 for metropolitan and 0 for suburban area),

$$a(h_\mathrm{r}) = (1.1\log_{10}(f_\mathrm{c}) - 0.7)h_\mathrm{r} - (1.56\log_{10}(f_\mathrm{c}) - 0.8), \qquad (4)$$

is the correction factor for a medium sized city.

The COST-WI LOS model is defined as:

$$\mathrm{P}_\mathrm{L}^\mathrm{WI}(d) = 42.6 + 26\log_{10}(d) + 20\log_{10}(f_\mathrm{c}). \qquad (5)$$

The channel model implemented in the OFDMA module in the ns-2 simulator is the path loss model described above combined with a Clarke-Gans implementation of Rayleigh Fading. Doppler effects are included to capture effects of node mobility and fast fading is included by modeling the channel as a Rayleigh fading channel with multiple taps as described by the ITU Pedestrian A model [15]. The path loss component is computed during simulation whereas the fast fading is computed prior to simulation.

Interference modelling in the ns-2 simulator is done at the subcarrier level by capturing packets from all transmitters in the system, both from secondary and primary nodes. When the received signal to interference plus noise ratio (SINR) on each subcarrier is calculated for each packet, a decision is made to further process or drop the packet. This is done by first finding the EESM (exponential effective SIR mapping) [4] to get the effective SINR and then extracting the block error rate (BLER) from the SINR, modulation and coding rate and block size. Based on the BLER value a decision is made whether to drop the packet or not. Please refer to [2] for details on the OFDMA implementation and interference modelling.

3.2 Primary System Transmit Power

The required transmit power P_t for the primary BS with antenna gain G_t when transmitting to a PU with antenna gain G_r at cell edge of a cell with radius r_p, is given by:

$$P_\mathrm{r} = P_\mathrm{t} + G_\mathrm{t} + G_\mathrm{r} - \mathrm{P}_\mathrm{L}(r_\mathrm{p}) - X, \qquad (6)$$

where $\mathrm{P}_\mathrm{L}(r_\mathrm{p})$ is the estimated path loss between BS and PU at cell edge with Eq. (2) and X is a gaussian distributed random variable with zero mean and standard deviation 8 dB representing shadow fading.

Due to limitations in the simulator, only omni-directional BS and user terminal antennas can be used. We therefore assume that both the BS and user terminal antenna have a gain of 0 dBi. As a result, the calculated transmission powers will be larger than in a real scenario with directional antennas.

The primary system uses QPSK modulation and forward error correction (FEC) coding rate 1/2, which requires a minimum received signal to noise ratio (SNR) $\frac{C_\mathrm{r}}{N} = 2.46$ dB. The primary system is assumed to be designed to have a cell edge coverage of 75%, which approximately corresponds to an area coverage of 90% [6]. The required received power at the PU in dBW is then:

$$P_\mathrm{r} = (\frac{C_\mathrm{r}}{N}) + N = \left(\frac{C_\mathrm{r}}{N}\right) + 10\log_{10}(kTB), \qquad (7)$$

where B is the bandwidth in Hz, k the Boltzmann constant and T the temperature in Kelvin.

The average path loss at cell edge is found by using Eq. 2 with center frequency $f_\mathrm{c} = 2$ GHz, BS height

$h_t = 30$ m, PU height $h_r = 1.5$ m and correction factor $C_M = 0$ since a medium sized city is considered, to be $P_L(1.15) = 139.9$ dB. The temperature is $T = 300$ K and utilized bandwidth is $B = 9189.6$ kHz. We assumed that both the BS and PU antenna gains are 0 dBi respectively. As a result, the calculated transmission powers will be larger than in a real scenario with directional antennas. With $G_t = 0$ dB and $G_r = 0$ dB, transmit power for the primary BS and the PU is:

$$P_t = P_L(r_p) + X + \left(\frac{C_r}{N}\right) + 10\log_{10}(kTB) \quad (8)$$
$$= 13.5\text{dBW}.$$

3.3 Sensor Threshold for Detecting the Primary Transmitters

In [12] it was required that a single sensor must be able to detect a user terminal with a probability of 0.95 (since there are many sensors the overall probability of detection will be higher). Assuming shadow fading with a standard deviation of 8 dB, the required shadow fading margin for 95% probability of detection is 13.16 dB. The threshold is then given by:

$$\text{Threshold} = P_t - P_L(r_{ws}) - 13.16\text{dB}, \quad (9)$$

where r_{ws} is the sensor radius. With 65 sensors per km^2 [11] each sensor covers an area of $1/65\,\text{km}^2$. Each side in the rectangle is $\frac{0.5}{\sqrt{65}} * 2 * 1000$ m and hence each sensor must cover a cell with radius $r_{ws} = 87.7$ m. By symmetry, both BS and PU transmit powers as found in Eq. 8 should be 13.5 dBW, so the threshold is:

$$\text{Threshold} = 13.5\text{dBW} - 82.8\text{dB} - 13.16\text{dB} \quad (10)$$
$$= -82.5\text{dBW}.$$

3.4 Requirement for Allowing Secondary Operation

In the simulator, the FC is responsible for allocating channels to the secondary system. A secondary BS or SU request a channel from the FC by sending its location and transmit power. The FC then calculates the interference range r_{int} for the querying SU as the minimum distance beyond which the generated interference is below a given limit [9, 10, 19]. Next, the FC checks if the received power for all sensors within r_{int} of the querying SU is below the threshold found in Eq. 11. If positive, the channel is reported as available for the SU. The interference limit used for calculating r_{int} is determined as follows:

> The interference generated to the primary system shall correspond to an increase of the noise-floor by less than 0.5 dB with a 90% probability.

which corresponds to a shadow fading margin of 10.3 dB. The interference range r_{int} thus satisfies:

$$P_t - P_L(r_{\text{int}}) + 10.3\text{dB} = \quad (11)$$
$$10\log_{10}(kTB) + 10\log_{10}(10^{\frac{0.5}{10}} - 1),$$

and the FC can now find the interference radius of the querying SU r_{int} as a function of P_t by using Eq. (6).

4 Simulation Setup

4.1 Simulation Scenario and Cases

The main goal of this study is to determine the performance for different cell sizes when considering costs for deployment of a secondary system when considering results from the business case analysis in [11]. Therefore three main cases with different cell sizes for the secondary system r_s will be considered, while primary cell size is $r_p = 1.15$ km:

(a) $r_s = r_p = 1.150$ km
(b) $r_s = \frac{2r_p}{3} = 0.767$ km
(c) $r_s = \frac{r_p}{2} = 0.575$ km

When considering the geometry of a hexagonal cell deployment we find that in case (a), theoretically 100% of the secondary BSs will be co-located with a primary BS, in (b) only 11.1% and in (c) 25%. Using the number of new sites into the business cases given in [11] for cases (b) and (c) will give negative business cases, however it should be argued that the smaller cells could require less complex and less expensive BS equipment and potentially also less expensive site costs. Even though the co-location factor of case (b) is smaller than that of case (c), the latter case will require more BSs to be deployed which also will give higher costs. It should also be noted that since there are limited amount of places to deploy BSs, case (a) will be favored due to the lower number of BSs that has to be deployed.

4.2 Simulation Parameters

Table 2 gives the values for the simulation and traffic setup. Constant bit rate (CBR) traffic is transmitted in the downlink (DL) for both the primary and secondary systems. Each single simulation is run 17 times on a modern computing cluster[1], with a duration of 500 s and warm up time of 20 s. The results are averaged.

[1] Each single simulation takes more than 1 hour on an IBM cluster with dual quad core compute nodes Xeon L5420 / 2.5 GHz processors, each with 8 cores, 8 GB of memory and operating system linux Ubuntu Hardy Heron.

Table 2 Selected simulation parameters

Parameter	Primary System	Secondary System
Traffic (DL)	CBR: 200 Kbps	CBR: 1 Mbps
Packet size	1500 Bytes	1500 Bytes
Nodes per BS	4	4
Nodes location	Random	Random
Nodes mobility	Rand. waypoint, speed 1-20 m/s	No
Cell radius (km)	1.15	0.575, 0.767, 1.15
Tx (dBW)	13.5	-40, -35, ... ,-5
Modulation/FEC	QPSK 1/2	QPSK 1/2

5 Analysis of Service Range and Coverage for the Secondary System

5.1 Secondary System Service Range

To get an indication of coverage we estimate the secondary system service range when using QPSK 1/2, which requires a minimum $\frac{C_r}{N} = 2.46\,\text{dB}$. We want to find the secondary cell radius r_s when having 75% coverage at cell edge when the required shadow fading margin is 5.39 dB. This will approximately correspond to an area coverage of 90%. r_s must satisfy:

$$P_t - P_L(r_s) - 5.39\text{dB} = 10\log_{10}(kTB) + \left(\frac{C_r}{N}\right). \quad (12)$$

Eq. (6) is used to find a function $r_s(P_t)$ for the estimated secondary coverage r_s as a function of P_t. The estimated range of the secondary system and interference range is plotted in Fig. 3(a). It can be observed that similar cell size for the primary and secondary systems will be difficult to achieve, at least with high probability of coverage at cell edge with transmit power 13.5 dBW. Hence, the secondary system must use much lower transmission powers than the primary system which will result in much lower coverage, hence it will be difficult to obtain coverage with similar cell size.

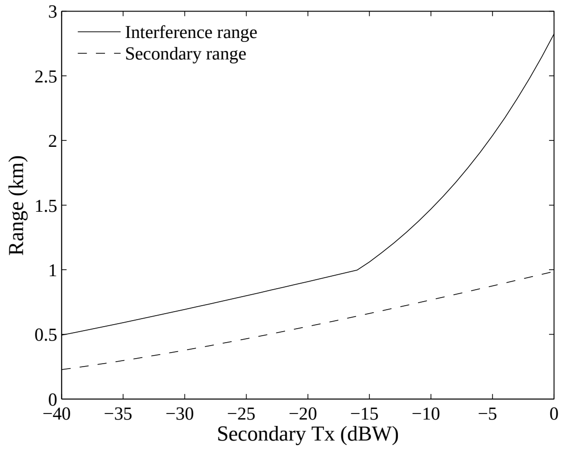
5.2 Probability of Coverage at Cell Edge

The probability of coverage at cell edge $P_{edge}[P_r(r_s) > P_{MIN}]$, where $P_{MIN} = 10\log_{10}(kTB) + \frac{C_r}{N}$ is the minimum required receiver threshold and σ is the standard deviation for shadow fading, is given by:

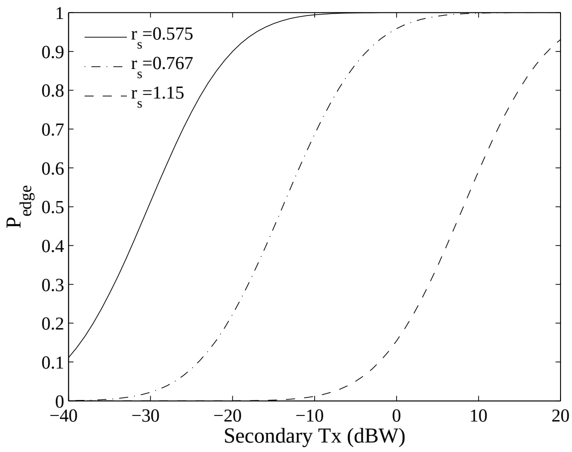
$$P_{edge}[P_r(r_s) > P_{MIN}] = Q\left(\frac{P_{MIN} - \overline{P_r(r_s)}}{\sigma}\right), \quad (13)$$

$$= \frac{1}{2} - \frac{1}{2}\text{erf}\left(\frac{P_{MIN} - (P_t - P_L(r_s))}{\sigma\sqrt{2}}\right),$$

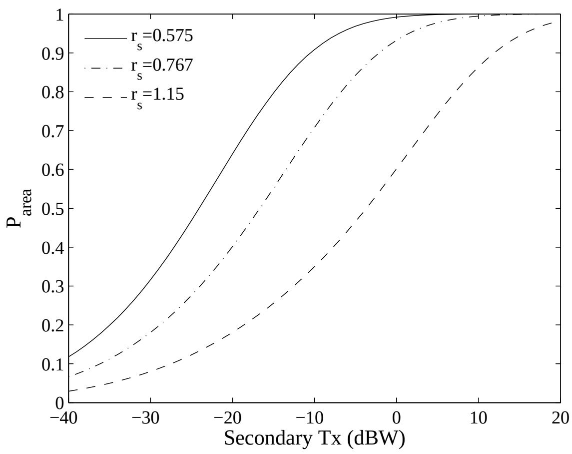
where $\sigma = 8\,\text{dB}$ and $\frac{C_r}{N} = 2.46\,\text{dB}$ (QPSK 1/2).



(a) Secondary service- and interference range



(b) Probability of coverage at cell edge



(c) Probability of area coverage

Fig. 3 Analysis of Service Range and Coverage for the Secondary System

Probability of coverage at cell edge as a function of transmit power P_t is plotted in Fig. 3(b) for secondary system radius $r_s = 0.575\,\text{km}$ and $r_s = 1.15\,\text{km}$. If we compare Fig. 3(b) with Fig. 3(a) it can be seen that it will be difficult to obtain good coverage at the cell edge for a secondary system with cell radius equal to the primary system cell radius. It can also be seen that if we reduce the secondary cell radius to half the primary cell radius, it is more likely that we are able to offer a service within that cell. However, this also depends on the level of interference from the primary system which also depends on the location of the primary users.

5.3 Probability of Area Coverage

When assuming a random location of the secondary nodes within the secondary cell, the probability of obtaining coverage in the cell, referred to as probability of area coverage, is given by:

$$\begin{aligned} &\mathrm{P_{area}}[\mathrm{P_r}(r_s) > P_{\mathrm{MIN}}] \qquad (14)\\ &= \int_0^{r_s} Q\left(\frac{P_{\mathrm{MIN}} - \overline{\mathrm{P_r}(r_s)}}{\sigma}\right) \frac{2\pi r}{\pi {r_s}^2}\,\mathrm{d}r,\\ &= \frac{2}{{r_s}^2} \int_0^{r_s} Q\left(\frac{P_{\mathrm{MIN}} - (P_t - \mathrm{P_L}(r_s))}{\sigma}\right) r\,\mathrm{d}r, \end{aligned}$$

where r_s is the cell edge coverage radius of the secondary system. The probability of area coverage is plotted in Fig. 3(c). If we compare with Fig. 3(a), it can be seen that there is high probability that coverage can be obtained for $r_s = 0.575\,\text{km}$, but that it will be more difficult with $r_s = 1.15\,\text{km}$.

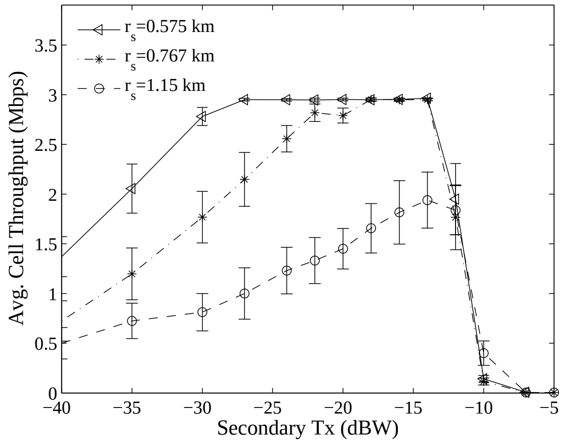
6 Performance Evaluation and Simulation Results

6.1 Evaluation of Different Cell Sizes for Cost Efficient Deployment in the Secondary System

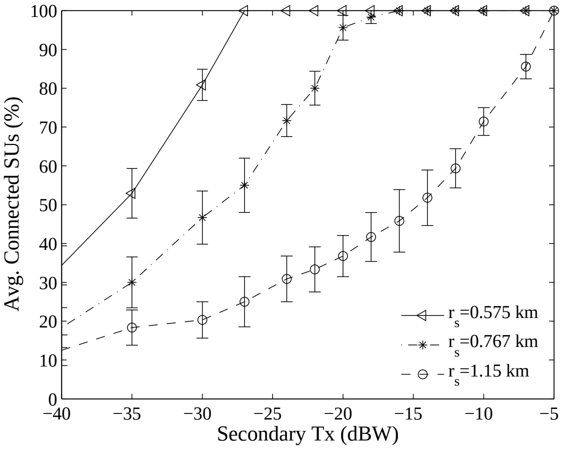
6.1.1 Performance of Secondary System

Average cell throughput for the secondary system measured at the transport layer for the three studied cases is plotted in Fig. 4(a) and the average number of SUs that obtained connectivity in Fig. 4(b).

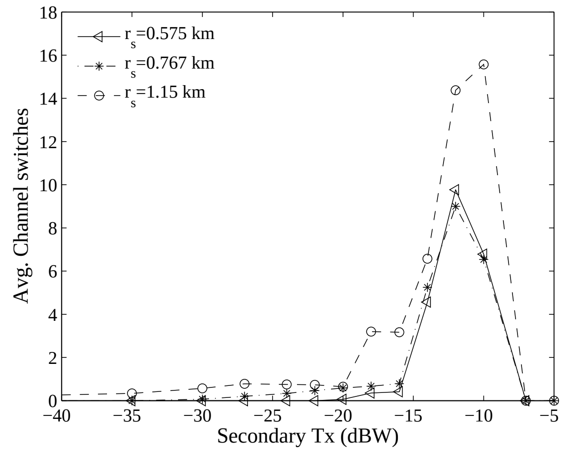
Maximum cell throughput was found to be close to 3 Mbps. A lower throughput is observed for the lower transmit power levels for all three cases which is due to the lower probability of obtaining connectivity as illustrated in Fig. 4(b). It can also be observed that in the cases with larger cell radius a lower percentage



(a) Avg. cell throughput of secondary system



(b) Average percentage of connected SUs

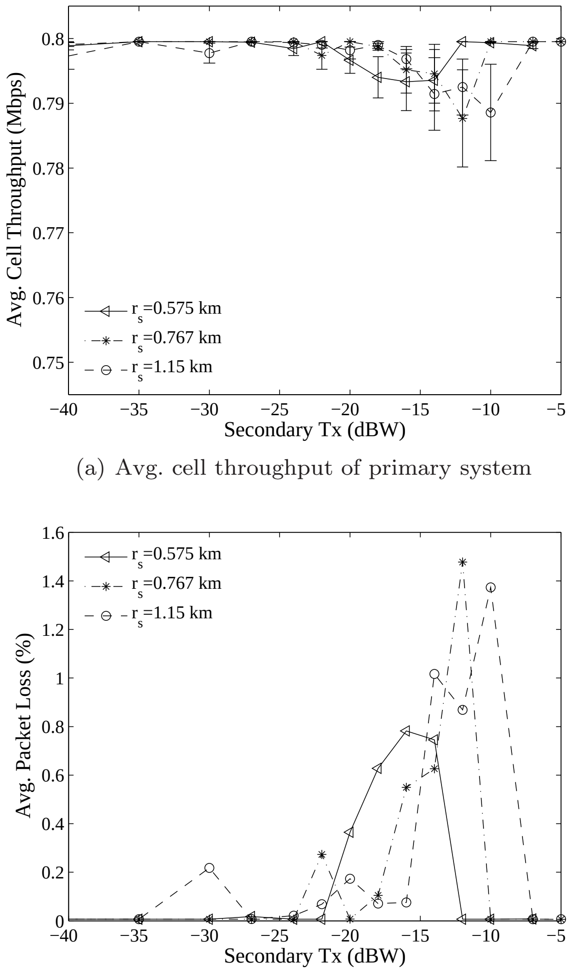


(c) Average number of channel switches

Fig. 4 Performance of the secondary system of the SUs obtain connectivity since the probability of being located at greater distances from the BS is higher, hence the throughput is lower. This is also confirmed by the analysis in Section 5. It should be noted that since the management traffic is communicated with BPSK modulation and FEC rate 1/2 the SUs might still obtain connectivity with the BS, but that the SNR can be too low to obtain service connectivity with QPSK 1/2.

Second it can be observed that the throughput reduces dramatically between -14 and -10 dBW for all three cases, which is because the probability of obtaining an available channel reduces since the interference range is higher for these higher transmit power levels. The case with $r_{\mathrm{s}} = 1.15$ does never obtain maximum throughput, whereas the other two cases does. This points in the direction of shorter range and smaller and less expensive BSs for the secondary system such as WiFi access points and femto-cells.

The average number of channel switches during the simulations plotted in Fig. 4(c) increases when interference range approaches the average distance between primary BS and PUs. Furthermore, the number of channel switches decreases rapidly when the probability of obtaining an available channel is reduced due to high interference range and hence there are no available channels.



(a) Avg. cell throughput of primary system

(b) Avg. Packet loss for PU

Fig. 5 Impact on primary system performance

6.1.2 Impact on Primary System

Average throughput measured at the transport layer for the primary system is plotted in Fig. 5(a). It can be seen that the throughput is quite stable for low secondary transmit power levels, but that throughput decreases more for high secondary transmit power levels. Also, a higher throughput reduction is in general observed for the cases with larger radius which is because the SUs are closer to the PUs leading to more severe interference. It should be noted that the primary system uses retransmissions to deal with channel errors and packet loss on the physical layer, hence the throughput does not explain the whole impact on the primary system.

Average percentage of packet loss for the primary system is given in Fig. 5(b), which shows that packet loss increases as secondary transmit power increases. Also, it can be seen that packet loss is about 50% lower for the case with $r_{\mathrm{s}} = 0.575$ than the cases with larger radius. Another observation is that packet loss increases as the amount of channel switches (Fig. 4(b)) in the secondary system increases, which is because there is some interference when a PU is within interference range but not yet detected due to intervals between sensing periods. Average packet loss per user does not exceed 1.6% which can be acceptable for best effort services in the primary system, but the performance of guaranteed bitrate remains to be tested.

Simulations were also run with traffic load 0.4 Mbps to each PU, but the impact on both primary and secondary system throughput and packet loss was similar as presented for 0.2 Mbps.

6.2 Evaluation of Increased Load in the Secondary System

To evaluate the impact of increased load in the secondary system, we focus on the case with $r_{\mathrm{s}} = 0.575$ km and run additional simulations for 8 and 12 PUs. Fig. 6 plots throughput measured at the transport layer for these three cases. A first observation is that throughput for cases with more SUs drops for lower transmit power levels since the probability that a PU is within interference range of a SU increases as the number of

SUs increases. A second observation is that maximum throughput is reduced since more of the resources are needed for management traffic at the link layer when the number of SUs increases. No major differences were observed with respect to packet loss nor on the impact on primary system performance. Third, the cell throughput is higher for the lower transmit power levels for cases with more SUs, which is because the probability increases that a sufficient number of SUs have a connection with SNR higher than the minimum SNR of 2.46 dB.

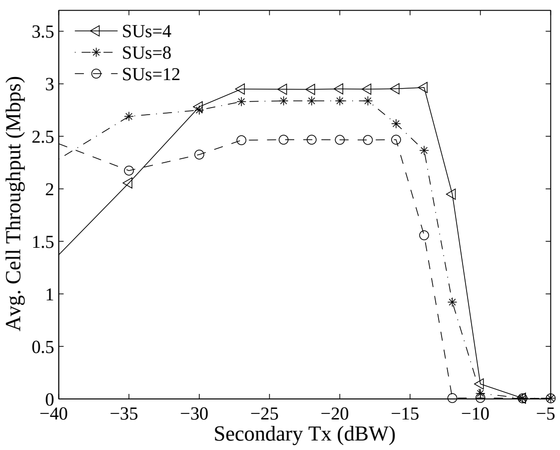


Fig. 6 Secondary system throughput for increasing number of PUs

7 Conclusions

This paper aimed at determining the performance for different cell sizes when considering the costs for deployment of the secondary system in an example SENDORA system when considering prior business case analysis, feasible deployment scenarios and the functionality of the total SENDORA system. Especially, secondary system performance and impact on the primary system was determined through simulations. First, it was found that equal cell size for the secondary and primary systems with a cellular reuse pattern with seven frequencies is difficult to achieve. Maximum achieved throughput was achieved with transmit power -14 dBW for all units when cell sizes are equal, however in average only about 50% of the secondary users obtained connectivity and the total system capacity was therefore not utilized. This does not fit together with results obtained in a prior business case analysis where co-location of secondary and primary BSs was shown to be very important since the cost of deploying new BS sites is expensive. Second, it was found that a good service could be offered with secondary cell size set to half the primary cell size and with restricted transmit power levels. The number of BSs installed will then be quadrupled and at least 75% of these would not be co-located with primary BSs leading to increased costs. This points in the direction of shorter range, smaller and less expensive BSs for the secondary system such as WiFi access points and femto-cells.

For further work, considering the above findings, it will be important to study alternative deployment scenarios such as cell sectorization and real deployments with non-hexagonal cells. Second, it will be interesting to study how a relaxed requirement to allow secondary operation will impact performance. Also, since the WSN is aware of the location of primary nodes, the requirement to allow secondary operation could be relaxed dynamically in situations where primary nodes have good connectivity. Finally, adaptive dynamic transmit power for the secondary system could increase performance.

Acknowledgements Part of the research leading to these results was performed in the SENDORA project (FP7/2007-2013, under grant agreement n° 216076).

References

1. Sendora project. URL `http://www.sendora.eu/`
2. The wimax forum system level simulator. URL `http://code.google.com/p/ns2-wimax-awg/`
3. Standard for local and metropolitan area networks part 16: Air interface for fixed and mobile broadband wireless access systems amendment 2: Physical and medium access control layers for combined fixed and mobile operation in licensed bands and corrigendum 1 (2006)
4. 3GPP TSG-RAN-1: Effective sir computation for ofdm system-level simulations. Tech. rep. (2003)
5. Axell, E., Larsson, E.G., Danev, D.: Capacity considerations for uncoordinated communication in geographical spectrum holes. Physical Communication **2**(1-2), 3 – 9 (2009). Cognitive Radio Networks: Algorithms and System Design
6. Braithwaite, C., Mike Scott: UMTS Network Planning and Development. Elsevier (2003)
7. Demosso, E.: COST 231. Digital mobile radio towards future generation systems. Final report. European Commission, EUR 18957. Brussels, Belgium (1999). URL `http://www.lx.it.pt/cost231`
8. FCC: ET Docket No. 10-237. Tech. rep. (2010)
9. Gastpar, M.: On capacity under received-signal constraints. In: In Proc 2004 Allerton Conference (2004)
10. Ghasemi, A., Sousa, E.S.: Fundamental limits of spectrum-sharing in fading environments. IEEE Transactions on Wireless Communications **6**(2), 649 –658 (2007)
11. Grøndalen, O., Lähteenoja, M., Grønsund, P.: Evaluation of business cases for a cognitive radio network based on wireless sensor network. In: New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on. Aachen, Germany (2011)

12. Grøndalen, O. et al.: Scenario descriptions and system requirements. Tech. rep. (2010)
13. Hayar, A. et al.: Performance of sendora networks. Tech. rep. (2011)
14. Hoven, N., Sahai, A.: Power scaling for cognitive radio. In: Wireless Networks, Communications and Mobile Computing, 2005 International Conference on, vol. 1, pp. 250 – 255 vol.1 (2005)
15. ITU: Guidelines for evaluations of radio transmission technologies for imt-2000. Tech. rep. (1997)
16. Larsson, E., Skoglund, M.: Cognitive radio in a frequency-planned environment: some basic limits. Wireless Communications, IEEE Transactions on **7**(12), 4800–4806 (2008)
17. Mercier, B. et al.: Sensor networks for cognitive radio: Theory and system design. In: ICT Mobile Summit. Stockholm, Sweden (2009)
18. Tandra, R., Sahai, A., Mishra, S.: What is a spectrum hole and what does it take to recognize one? Proceedings of the IEEE **97**(5), 824 –848 (2009)
19. Wang, C.X., Hong, X., Chen, H.H., Thompson, J.: On capacity of cognitive radio networks with average interference power constraints. Wireless Communications, IEEE Transactions on **8**(4) (2009)

Paper D
Evaluation of Interference Requirements in a Sensor Aided Cognitive Radio System

Pål Grønsund and Ole Grøndalen

Proceedings of the 54th IEEE Global Communications Conference (IEEE GLOBECOM), Houston, Texas, US, Dec. 3-7, 2011.

Evaluation of Interference Requirements in a Sensor Network Aided Cognitive Radio System

Pål Grønsund*† and Ole Grøndalen*
*Telenor, Snarøyveien 30, 1331 Fornebu, Norway
†Department of Informatics, University of Oslo, Gaustadallen 23, 0373 Oslo, Norway
Email: *{pal.gronsund, ole.grondalen}@telenor.com, †paalrgr@ifi.uio.no

***Abstract*—To better exploit the spectrum resources a wireless sensor network can be used to assists a secondary cognitive radio network by providing information about the current primary spectrum occupancy. In this paper we study the performance of the secondary network when it is co-located with and having similar cell size as a mobile primary network that uses a cellular reuse pattern with seven frequencies. Especially we study how relaxed requirements for the maximum interference generated by the cognitive radios affect the performance of the secondary and primary network in terms of throughput, packet loss, delay, coverage and connectivity. We show that it is possible to find interference limits for the cognitive radio that allow full throughput and coverage for the secondary system at the cost of a slight reduction in throughput and an increase in packet loss per user of 2% on average for the primary system.**

I. Introduction

In the EU FP7 project SENDORA [1] a novel concept denoted sensor network aided cognitive radio was coined and developed. The main idea is to use a wireless sensor network (WSN) to assist a cognitive radio network by providing information about the current primary spectrum occupancy. In this paper we refer to such systems as SENDORA systems. The WSN can be embedded in the cognitive radio devices and be deployed as a separate network. An embedded solution is also envisioned and desired for higher detection probability [2]. Input on such real time spectrum monitoring by using a separate low cost WSN was recently requested by FCC [3].

A business case study in [4] found that a high degree of co-location of secondary and primary base stations (BSs) was one of the most critical requirements for achieving a positive business case. Following this study, a technical study in [5] found that co-location and equal cell size for the secondary and primary systems with cellular reuse pattern with seven frequencies is difficult to achieve, but that a good service could be offered with secondary cell size set to half the primary cell size and restricted transmit power levels. Since the latter requires 75% new BS sites to be deployed it conflicts with the assumptions made in the business case analysis. In the proposed business model where primary spectrum owners establish a joint venture that uses the available spectrum on a secondary basis, the primary operator economical benefits from high secondary system performance. Therefore the primary operators are expected to be willing to accept higher levels of interference from the secondary system. One way to substantially increase cash flow for the secondary system is to reduce costs by using similar cell size and hence maximize co-location with the primary system. This can be achieved by relaxing the limits for the maximum interference the secondary system is allowed to generate into the primary system.

In this paper we study the possibility of using the same cell size for the secondary system as for the primary system by relaxing the limit for how much interference the secondary system can generate [6]–[9]. The SENDORA system is implemented in the network simulator ns-2 where all parts of the SENDORA system are implemented; a primary network, a centralized secondary network, a WSN and a centralized fusion centre (FC) which aggregates spectrum usage information from the sensors. Realistic network topologies, traffic models and the whole protocol stack of the secondary and primary systems with actual transport, network, link and physical layers are implemented in the simulator to give a detailed picture of the high level network performance of both the secondary and primary networks.

The main contribution of this paper is the performance study of how relaxed interference requirements can increase secondary system performance and how this impacts primary system performance in terms of throughput, packet loss, delay, coverage and connectivity. It should be noted that the focus of this paper is on estimating realistic network performance and not on optimization of algorithms.

II. System Model

The SENDORA system illustrated in Fig. 1 consists of four main systems; the primary network which in this case is WiMAX, the secondary network which in this case is a modified version of WiMAX with SENDORA functions implemented, the WSN and the centralized FC. Each of these networks will be described in the subsequent sections.

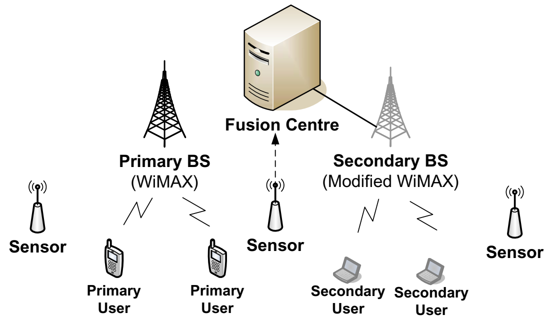


Fig. 1. Illustration of system model

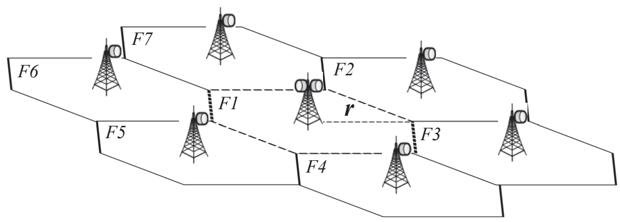


Fig. 2. Illustration of network model

To obtain an available channel the secondary network consults the FC which has the total responsibility for communicating with the WSN. The simulation model for the primary and secondary networks uses an ns-2 implementation of WiMAX [10] developed in WiMAX Forum. The FC and WSN are also implemented in ns-2.

A. Network Model

The considered network model is illustrated in Fig. 2. The primary system uses a three-cell reuse pattern with 7 BS cells with frequencies $F1$ to $F7$ in the 2 GHz band. The secondary system consists of 1 BS cell co-located with a primary BS as illustrated by the BS with two antennas in Fig. 2. The secondary BS and its SUs will use one of the frequencies $F2$ to $F7$ if available, where $F1$ not will be used because the primary nodes of that cell are within interference range. The WSN and FC are not illustrated in Fig. 2. For both primary and secondary systems, BS heights are 30 m and subscriber station heights 1.5 m. The distance between primary BSs is 2 km. The cells are hexagonal with a radius of 1.15 km. It is assumed that the primary system is noise limited. There are 65 sensors/km^2 [4].

B. Path Loss and Channel Model

In the 2 GHz frequency band, the COST 231 Hata model [11] is valid for distances above 1 km and the Cost Walfish-Ikegami (WI) [11] for distances below 1 km. A path loss model which agrees with the COST-WI line-of-sight model, $P_L^{WI}(d)$, for short distances d and with the COST Hata model, $P_L^{Hata}(d)$, at distance above 1 km is used:

$$a = P_L^{WI}(1\,km),$$
$$b = P_L^{Hata}(1\,km),$$

$$P_L(d) = \begin{cases} P_L^{WI}(d) + d(b-a), & d < 1km, \\ P_L^{Hata}(d), & d \geq 1km \end{cases} \quad (1)$$

The channel model implemented in the OFDMA module in the ns-2 simulator is the path loss model described above combined with a Clarke-Gans implementation of Rayleigh Fading. Doppler effects are included to capture effects of node mobility and fast fading is included by modeling the channel as a Rayleigh fading channel with multiple taps as described by the ITU Pedestrian A model [12]. The path loss component is computed during simulation whereas the fast fading is computed prior to simulation.

Interference modeling in the ns-2 simulator is done at the subcarrier level by capturing packets from all transmitters in the system, both from secondary and primary nodes. When the received signal to interference plus noise ratio (SINR) on each subcarrier is calculated for each packet, a decision is made to further process or drop the packet. This is done by first finding the EESM (exponential effective SIR mapping) [13] to get the effective SINR and then extracting the block error rate (BLER) from the SINR, modulation and coding rate and block size. Based on the BLER value a decision is made whether to drop the packet or not. Please refer to [10] for details on the OFDMA implementation and interference modeling.

TABLE I
PARAMETERS FOR BOTH PRIMARY AND SECONDARY SYSTEMS

Parameter	Value
Frequency	2 GHz
Channel bandwidth	10 MHz
FFT size	1024
Duplexing method	Time Division Duplex (TDD)
OFDMA Frame size	5 ms
DL:UL ratio	2:1
Modulation types	BPSK, QPSK, 16-QAM, 64-QAM
FEC rates	1/2, 2/3, 3/4
Cyclic prefix mode	1/4
OFDM mapping	Vertical striping
Total subcarriers used	840
Guard and null subcarriers	184
Pilot subcarriers	DL: 120, UL: 280
Data subcarriers	DL: 720, UL: 560
Subcarriers/subchannel	DL: 28, UL: 24
Subchannels	DL: 30, UL: 35
OFDMA symbols per frame	43
Subcarrier allocation	Partially Used Subcarrier Allocation

III. PRIMARY SYSTEM

The primary WiMAX system, based on IEEE 802.16e [14], implemented in ns-2 includes a very detailed model of the MAC and also a good model of the PHY layers. The main parameters given in Table I are common for the primary and secondary systems. WiMAX uses orthogonal frequency division multiple access (OFDMA) and time division duplex (TDD). Operating frequency is in the 2 GHz band and the channel bandwidth is 10 MHz with a total of 1024 subcarriers.

The required transmit power P_t for the primary BS with antenna gain G_t when transmitting to a PU with antenna gain G_r at cell edge of a cell with radius r, is given by:

$$P_r = P_t + G_t + G_r - P_L(r) - X, \quad (2)$$

where $P_L(r)$ is the estimated path loss by Eq. (1) between BS and PU at cell edge and X is a gaussian distributed random variable with zero mean and standard deviation of $\sigma = 8$ dB representing shadow fading.

The primary system uses QPSK modulation and forward error correction (FEC) coding rate $1/2$, which requires a minimum received signal to noise ratio (SNR) $\frac{C_r}{N} = 2.46$ dB. The primary system is assumed to be designed to have a cell edge coverage of 75%, which approximately corresponds to an area coverage of 90% [15]. The required received power at the PU is then:

$$P_r^{dBW} = \left(\frac{C_r}{N}\right)^{dB} + N^{dBW} = \left(\frac{C_r}{N}\right)^{dB} + 10log_{10}(kTB), \quad (3)$$

where B is the bandwidth in Hz, k the Boltzmann constant and T the temperature in Kelvin.

The average path loss at cell edge is found by using Eq. (1) with center frequency $f_c = 2\,\text{GHz}$, BS height $h_t = 30\,\text{m}$, PU height $h_r = 1.5\,\text{m}$ and correction factor $C_M = 0$ since a medium sized city is considered, to be $P_L(1.15km) = 139.9\,\text{dB}$. The temperature is $T = 300\,\text{K}$ and utilized bandwidth is $B = 9189.6\,\text{kHz}$. Due to limitations in the simulator, only omni-directional BS and user terminal antennas can be used. We therefore assume that both the BS and PU antenna gains are 0 dBi respectively. As a result, the calculated transmission powers will be larger than in a real scenario with directional antennas. With $G_t = 0\,\text{dB}$ and $G_r = 0\,\text{dB}$, transmit power for the primary BS and the PU is:

$$P_t^{dBW} = P_L(r)^{dB} + X^{dB} + \left(\frac{C_r}{N}\right)^{dB} + 10log_{10}(kTB) = 13.5\,dBW. \tag{4}$$

IV. Wireless Sensor Network and Fusion Centre

A. Wireless Sensor Network Functionality and Parameters

The WSN provides information about spectrum occupancy in the area where the secondary network is deployed. The WSN is deployed in a rectangular grid and each sensor senses all the primary frequency bands. Furthermore, the sensors are simple energy detectors, thus synchronization of quiet periods between the WSN and secondary network is important. The sensing period is 30 milliseconds which is repeated with 0.5 second intervals. After each sensing period, the WSN communicates its sensing result to the FC responsible for allocating frequencies to the secondary system. A common control channel is used for reporting sensing measurements.

In [16] it was required that a single sensor must be able to detect a user terminal with a probability of 0.95 (since there are many sensors the total probability of detection will be much higher). Assuming shadow fading with a standard deviation of 8 dB, the required shadow fading margin for 95% probability of detection is 13.16 dB. The threshold is then given by:

$$Threshold^{dBW} = P_t^{dBW} - P_L(r_{ws})^{dB} - 13.16\,dB, \tag{5}$$

where r_{ws} is the wireless sensor radius. With 65 sensors/km^2 [4] each sensor covers a rectangular area of 1/65 km^2. Each side in the rectangle is then $\frac{0.5}{\sqrt{65}} * \sqrt{2} * 1000\,\text{m}$ and hence each sensor must cover a cell with radius $r_{ws} = 87.7\,\text{m}$. By symmetry, both the BS and PU transmit power as found in Eq. (4) should be 13.5 dBW, so the threshold is:

$$Threshold^{dBW} = 13.5\,dBW - 82.8\,dB - 13.16\,dB = -82.5\,dBW. \tag{6}$$

B. Fusion Centre Functionality and Parameters

The FC collects information from the sensors and will at any time have a near real-time overview of the spectrum occupancy for the area covered by the WSN. Upon spectrum request from the secondary system, the FC uses an algorithm that consults a matrix, representing the sensors in the WSN, that contain spectrum usage measurements for all potential channels from all sensors. Required functions for receiving sensor reports, calculating the spectrum map, managing allocations and communicate with the secondary system are implemented in the FC. The channel allocation algorithm allocates one of the available channels not used by the primary system.

In the simulator, the FC calculates the interference range r_{int} for the querying SU as the minimum distance beyond which the generated interference is below a given limit [6]–[9]. Next, the FC checks if the received power for all sensors within r_{int} of the querying SU is below the threshold found in Eq. (6). If positive, the channel is reported as available for the SU. The interference limit used for calculating r_{int} is determined as follows: *the interference generated to the primary system should correspond to an increase of the noise-floor of less than 0.5 dB with a certain probability P_N.*

For this interference requirement, the interference radius r_{int} should satisfy:

$$P_t^{dBW} - P_L(r_{int})^{dB} + \alpha^{dB} = 10log_{10}(kTB) + 10log_{10}(10^{\frac{0.5}{10}} - 1), \tag{7}$$

where α is the fading margin required to achieve a given P_N. The interference range as a function of transmitted power $r_{int}(P_t)$ can be found by using Eq. (2).

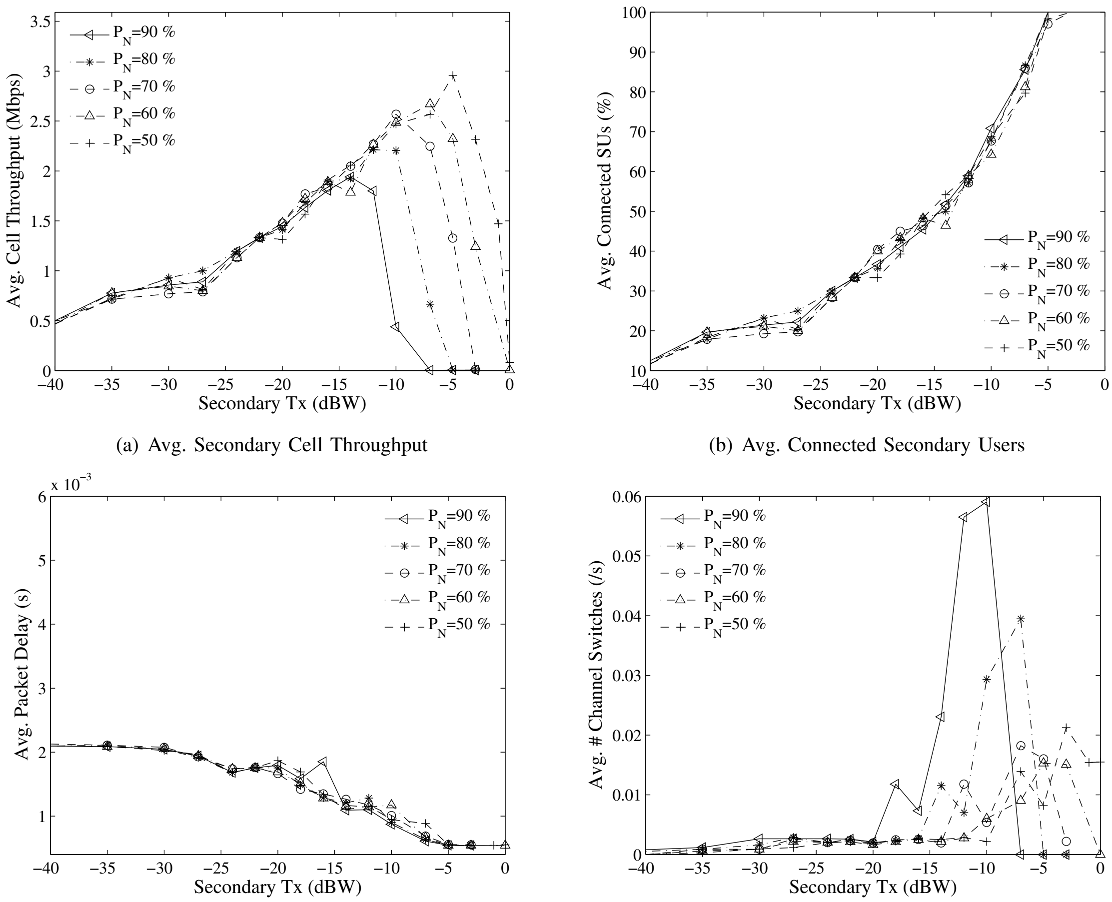
V. Secondary System

The secondary network is also based on WiMAX and the ns-2 simulator model developed in WiMAX Forum. The simulator model was modified with required functionality for operation as a secondary cognitive radio network. A centralized network with a single cell, a single BS and a set of SUs is considered. Two main cognitive functions are implemented. The first is a cognitive actuation module that communicates with the FC to obtain an available frequency allocation and then actuates this in the secondary network. The second is time synchronization with the WSN for quiet periods during which the WSN can measure primary activity.

To obtain an available channel the secondary system communicates with the FC which communicates with the sensors. First, the secondary BS queries the FC to obtain an available frequency and then informs the SUs about its allocated frequency. Next, since the BS is unaware of the SU coverage area, the SUs also need to query the FC if the frequency allocated to the BS is available for it. If not, the affected SU notifies the BS which queries the FC for a new frequency.

VI. Performance Evaluation

Simulations are run with co-located primary and secondary BS and equal cell size $r = 1.15\,\text{km}$ for different requirements to allow secondary operation with $P_N = 90, 80, 70, 60$ and 50%, which corresponds to the fading margins $\alpha = 10.25, 6.73, 4.20, 2.03$ and 0 dB respectively. Each of these are run for increasing secondary transmit power in the range -40, -35, ... ,-5 dBW. Selected values for simulation and traffic setup are given in Table II, where it can be seen that constant bit rate (CBR) traffic is transmitted in the downlink (DL).



(a) Avg. Secondary Cell Throughput

(b) Avg. Connected Secondary Users

(c) Avg. Secondary User Delay

(d) Avg. Secondary Channel Switches

Fig. 3. Performance of the secondary system

Each simulation is run 15 times, with a duration of 500 s and warm up time of 20 s to ensure that a stable point of network operation is reached. The results are averaged.

TABLE II
SELECTED PARAMETERS FOR THE SIMULATION RUNS AND TRAFFIC SETUP

Parameter	Primary System	Secondary System
Traffic per node	DL CBR: 0.2 Mbps	DL CBR: 1 Mbps
Packet size	1500 B packets	1500 B packets
Nodes per BS	4	4
Nodes location	Random location	Random location
Nodes mobility	Random waypoint random speed 1-20 m/s	No
Cell radius	1.15 km	1.15 km
Transmit power	13.5 dBW	-40, -35, ... ,-5 dBW
Modulation/FEC	QPSK 1/2	QPSK 1/2

A. Secondary System Performance

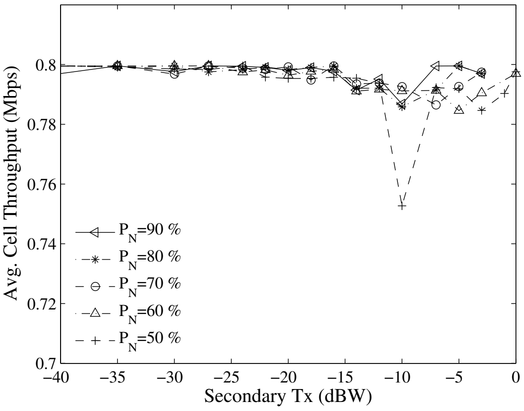
Average throughput for the secondary system is plotted in Fig. 3(a) as a function of secondary transmit power. It can be seen that throughput increases as the limit for the maximum interference generated by secondary operation is relaxed. The reason for this increase in throughput is that the interference range of the secondary transmitter is reduced as the requirement is relaxed. It can also be seen that the secondary system throughput decreases rapidly towards the end since interference range increases and hence the probability of obtaining an available channel is reduced. This indicates that the secondary system coverage and throughput is limited by interference range which depends on the requirement to allow secondary operation. The low throughput for lower transmit power levels is because the probability of obtaining coverage is lower as illustrated in Fig. 3(b), which not reaches 100% before $T_X = -5\,\text{dBW}$.

From the average packet delay at the network layer including queuing delay for the secondary system plotted in Fig. 3(c), it can be seen that delay decreases as transmit power increases. The reason for this is that higher transmit power gives a better link budget and less retransmissions.

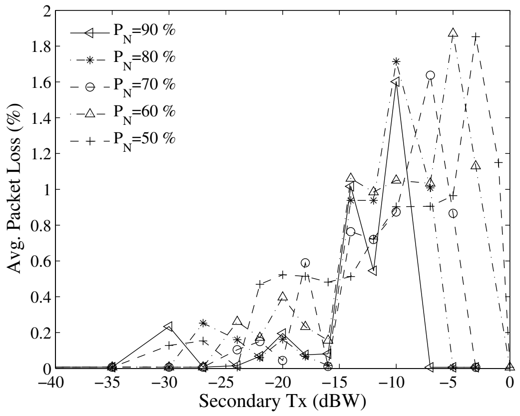
The average number of channel switches during the simulations plotted in Fig. 3(d) increases when interference range approaches the average distance between primary BS and PUs, and decreases rapidly when the probability of obtaining an available channel is reduced due to high interference range.

B. Primary System Performance

Average throughput for the primary system is plotted in Fig. 4(a). It can be seen that the throughput is quite stable for lower secondary transmit power levels, but that throughput



(a) Avg. Primary Throughput



(b) Avg. Primary User Packet Loss

Fig. 4. Performance of the primary system

decreases more for higher secondary transmit power levels. A higher throughput reduction is also in general observed for the more relaxed requirements to allow secondary operation. It should be mentioned that the primary system uses retransmissions to deal with channel errors and packet loss on the physical layer, hence the throughput does not explain the whole impact on the primary system.

Average percentage of packet loss for the primary system is plotted in Fig. 4(b). It can be seen that packet loss increases as secondary transmit power increases. It can also be seen that the percentage of packet loss is slightly higher for the more relaxed requirements for allowing secondary operation. The peaks in packet loss for the different requirements are shifted to the right, which is due to the shorter interference range for lower limits on the maximum allowed interference generated from the secondary system. It can also be seen that packet loss increases, especially as the amount of channel switches in the secondary system increases (Fig. 3(d)). This is because there is some interference when a PU is within interference range but not yet detected due to intervals between sensing periods. Average packet loss per user does not exceed 2% which can be acceptable for best effort services in the primary system, but the performance of guaranteed bitrate remains to be tested.

Average packet delay at the network layer including queuing delay for the primary system was found to be 0.51 ms without major variations nor major impact from the secondary system.

VII. Conclusions

In this paper an example of a sensor network aided cognitive radio system were studied, where the secondary network is co-located with and having similar cell size as a mobile primary system that uses a cellular reuse pattern with seven frequencies. Especially it was studied how relaxed requirements for the maximum interference generated by the secondary transmitters can improve secondary system performance and impact on primary system performance. It was found that allowing higher interference, max throughput and full coverage can be obtained. It was also found that this comes at the costs of a decrease in primary system performance with a slight reduction in throughput and increased packet loss per user of 2% on average. This can be considered acceptable for a business model where the primary operator gets economical benefits from improved secondary system performance.

Acknowledgment

The research leading to these results was performed in the SENDORA project (FP7/2007-2013, under grant agreement n° 216076).

References

[1] “Sendora project.” [Online]. Available: http://www.sendora.eu/
[2] V. Fodor et al., “Sensor networks for cognitive radio: Theory and system design,” in *ICT Mobile Summit*, Stockholm, Sweden, Jun. 10–12, 2009.
[3] FCC, “ET Docket No. 10-237,” Notice of Inquery, November 30 2010.
[4] O. Grøndalen, M. Lähtenooja, and P. Grønsund, “Evaluation of business cases for a cognitive radio network based on wireless sensor network,” in *Accepted to IEEE DySPAN 2011*, Aachen, Germany, May 3–6, 2011. [Online]. Available: http://bit.ly/hU6HYU
[5] A. Hayar et al., “Performance of sendora networks,” SENDORA Report, January 2011.
[6] M. Gastpar, “On capacity under received-signal constraints,” in *In Proc 2004 Allerton Conference*, 2004.
[7] A. Ghasemi and E. Sousa, “Fundamental limits of spectrum-sharing in fading environments,” *Wireless Communications, IEEE Transactions on*, 2007.
[8] ——, “Capacity of fading channels under spectrum-sharing constraints,” in *IEEE ICC*, june 2006.
[9] C.-X. Wang, X. Hong, H.-H. Chen, and J. Thompson, “On capacity of cognitive radio networks with average interference power constraints,” *Wireless Communications, IEEE Transactions on*, 2009.
[10] “The wimax forum system level simulator.” [Online]. Available: http://code.google.com/p/ns2-wimax-awg/
[11] E. Demosso, *COST 231. Digital mobile radio towards future generation systems. Final report*. European Commission, EUR 18957. Brussels, Belgium, 1999. [Online]. Available: http://www.lx.it.pt/cost231
[12] ITU ITU-R M.1225, “Guidelines for evaluations of radio transmission technologies for imt-2000,” 1997.
[13] “Effective SIR computation for OFDM system-level simulations,” 3GPP-TSG-RAN-1, Tech. Rep. RI-03-1370, 2003.
[14] *Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1*, IEEE Std. 802.16e, Apr. 2006.
[15] C. Braithwaite and Mike Scott, *UMTS Network Planning and Development*. Elsevier, 2003.
[16] O. Grøndalen et al., “Scenario descriptions and system requirements,” SENDORA Report, June 2010.

Paper E
Business Case Evaluations of LTE Network Offloading with Cognitive Femtocells

Pål Grønsund, Ole Grøndalen and Markku Lähteenoja

Telecommunications Policy (JTPO), vol. 37, no. 2-3, pp. 140-153, Mar.-Apr. 2013.

Telecommunications Policy 37 (2013) 140–153

Contents lists available at SciVerse ScienceDirect

Telecommunications Policy

URL: www.elsevier.com/locate/telpol

Business case evaluations for LTE network offloading with cognitive femtocells

Pål Grønsund [a,b,*], Ole Grøndalen [a], Markku Lähteenoja [a]

[a] Telenor, Snarøyveien 30, 1331 Fornebu, Norway
[b] Department of Informatics, University of Oslo, Gaustadallen 23, 0373 Oslo, Norway

ARTICLE INFO

Available online 27 October 2012

Keywords:
Cognitive radio
Business case
LTE
Cognitive femtocell
Sensor network
TV white spaces

ABSTRACT

Mobile networks are increasingly becoming capacity limited such that more base stations and smaller cells or more spectrum are required to serve the subscribers' increasing data usage. Among several challenges, the establishment of new base station sites becomes challenging and expensive. This study proposes and analyzes critical aspects of a business case where a mobile operator offloads its mobile LTE network by deploying cognitive femtocells. When aided by a sensor network the cognitive femtocell will be able to use frequencies other than the mobile network and hence increase its power to cover outdoor areas and neighbour buildings. This cognitive femtocell strategy will be compared with an alternative strategy where an operator deploys conventional femtocells and has to build additional base stations to meet the traffic demands. The business case analysis illustrates that there is a potential for cost savings when offloading the mobile network with cognitive femtocells when compared to the alternative strategy. It must be emphasized that the studied concept is innovative and that the business case period starts in 2017, hence, parameter assumptions are uncertain. Therefore, as the most important message of this work, sensitivity analysis is used to reveal the most critical aspects of the cognitive femtocell business case. It is found that the most critical parameters regarding the cognitive femtocell are the price for backhauling, the number of users supported and the coverage. Furthermore, an optimal coverage radius for the cognitive femtocell for lowest possible costs is found. Costs related to the fixed sensor network are found to be less critical since sensors are embedded in the cognitive femtocells. Sensitivity analysis is also presented for spectral efficiency, cognitive and conventional femtocell offloading gain, sensor density and price, customer density and price for base station site establishment.

1. Introduction

Several measurement campaigns have demonstrated that radio spectrum is underutilized (FCC, 2002). The main application for cognitive radio (CR) is to exploit the spectrum resources more efficiently by opportunistically utilizing radio spectrum not utilized by primary networks, referred to as spectrum holes (Tandra, Sahai, & Mishra, 2009). More than 10 years of research on CR (Pawelczak, Nolan, Doyle, Oh, & Cabric, 2011) has resulted in innovative and promising

* Corresponding author at: Telenor, Snarøyveien 30, 1331 Fornebu, Norway. Tel.: +47 93856442; fax: +47 67892199.
E-mail addresses: pal.gronsund@telenor.com (P. Grønsund), ole.grondalen@telenor.com (O. Grøndalen), markku.lahteenoja@telenor.com (M. Lähteenoja).

0308-5961/$ - see front matter
http://dx.doi.org/10.1016/j.telpol.2012.07.006

technologies such as opportunistic spectrum access (Zhao & Sadler, 2007) and spectrum sensing (Yucek & Arslan, 2009). When considering recent advances in regulations to allow opportunistic access to the UHF bands by the US regulator FCC (2008, 2010) and the UK regulator Ofcom (2009), referred to as TV White Spaces (TVWS), CR now seems to approach commercialization. Several networking scenarios have been identified for use of CR in TVWS such as mobile, WiFi, femtocell, mesh, ad hoc, machine-to-machine and smart-grid communication (Wang, Ghosh, & Challapali, 2011).

A promising technology for CR referred to as a sensor network aided cognitive radio system was proposed in the EU FP7 project SENDORA (Mercier et al., 2009), where external sensors in addition to sensors embedded in terminals are used to detect primary users. The usage of externally deployed sensors will significantly improve the system's ability to detect primary users compared to CR solutions based on sensing performed by terminals only and at the same time optimize utilization of spectrum holes.

Three business case scenarios for deployment of a SENDORA system were proposed and evaluated in Grøndalen, Lähteenoja, and Grønsund (2011) - a spectrum sharing, a spectrum broker and a new entrant business case scenario. Critical parameters influencing profitability were highlighted such as the required density of fixed sensors which strongly depends on the interference limits set to protect primary operators. A second critical parameter was the fixed sensor operational costs which indicate that the fixed sensor power consumption must be low and that the mean time between failures must be long. The business cases showed that there is a potential to do business using the SENDORA concept, but that more research and development is needed with respect to the critical parameters highlighted. It is shown in Weiss, Altamimi, and Cui (2012) that operating context matters when it comes to choosing an appropriate technology for context awareness, and that solutions based on databases or cooperative sharing with explicit communication between primary and secondary users are the most suitable approaches in static environments such as TV white spaces. It is also shown that external sensor networks is the least cost effective. However, it should be noted that sensing might be required by the regulator in some markets to for example, reliably detect wireless microphones, and can be used by the secondary operator to control the interference generated and can thereby free more white space spectrum as decisions are based on actual measurements instead of predictions.

Mobile networks are increasingly becoming capacity limited such that more base stations (BSs) and smaller cells are required to serve the subscribers. Operators might then have to build new BS sites which when considering costs for equipment, site rental, backhaul, power consumption and site acquisition becomes expensive. Another alternative is to acquire more spectrum, but this might not always be feasible. A promising alternative is to deploy femtocells (Chandrasekhar, Andrews, & Gatherer, 2008; Claussen, Ho, & Samuel, 2008) within people's homes and businesses to offload the macro network. With increased transmit power, these femtocells would also cover areas outside the buildings. However, since femtocells most often use the same frequency as the macro network, interference management with the macro network becomes challenging (Choi, Monajemi, Kang, & Villasenor, 2008). This leads to the idea of cognitive femtocells able to opportunistically detect and utilize spectrum holes (Gür, Bayhan, & Alagöz, 2010; Xiang, Zhang, Skeie, & Xie, 2010) by using sensing (Harjula & Hekkala, 2011) to improve coverage and spectral efficiency (Riihijarvi, Nasreddine, & Mahonen, 2011). It is stated in Chapin and Lehr (2011) that the future for high quality mobile broadband competition will require significantly more sharing among commercial mobile radio service operators of both infrastructure and spectrum, and that a key driver to achieve this is the need to shrink cell sizes that will support efficient spatial reuse of spectrum and lower power operation.

The main contribution of this work is the proposal and evaluation of a business case that uses cognitive femtocells to address the challenges with building smaller cells to offload capacity limited networks. The idea and strategy is that the mobile operator offloads its mobile LTE network by deploying cognitive femtocells using the SENDORA concept. Generally, a femtocell covers an indoor area of around 10 m to improve indoor coverage (Weitzen & Grosch, 2010), but when aided by a sensor network the cognitive femtocell will be able to use frequencies other than the mobile network and hence increase its power to cover outdoor areas and neighbour buildings (Kawade & Nekovee, 2011). As a result, the cognitive femtocell is turned into a picocell and at the same time reduce or remove the costs when deploying additional BSs. This study builds on the work presented in Grøndalen et al. (2011) by reusing the results on sensor network density analysis and some of the results on cost estimation. The novelty of this study is the proposal and evaluation of a completely new business case and scenario with cognitive femtocells using the SENDORA concept to offload the macro network.

The main goal of this study is to compare a novel strategy of using cognitive femtocells and the SENDORA concept to offload an existing macro network to a strategy of using conventional femtocells in combination with building new BSs. The comparison is done to estimate the potential cost savings and to identify the most critical aspects of the novel approach.

2. Sensor network aided cognitive radio system overview and architecture

The SENDORA technology utilizes wireless sensor networks (WSNs) to support the coexistence of licensed and unlicensed wireless users in an area, and the SENDORA scenario constitutes of three main networks; the primary (usually licensed) network, the secondary network and the WSN. This scenario is depicted in Fig. 1, where the network of CR users, called the secondary network, exchange information with the WSN. The WSN monitors the spectrum usage, and is thus aware of the spectrum holes that are currently available and can potentially be exploited by the secondary network. This information is provided back to the secondary network which is then able to communicate without causing harmful interference to the primary network.

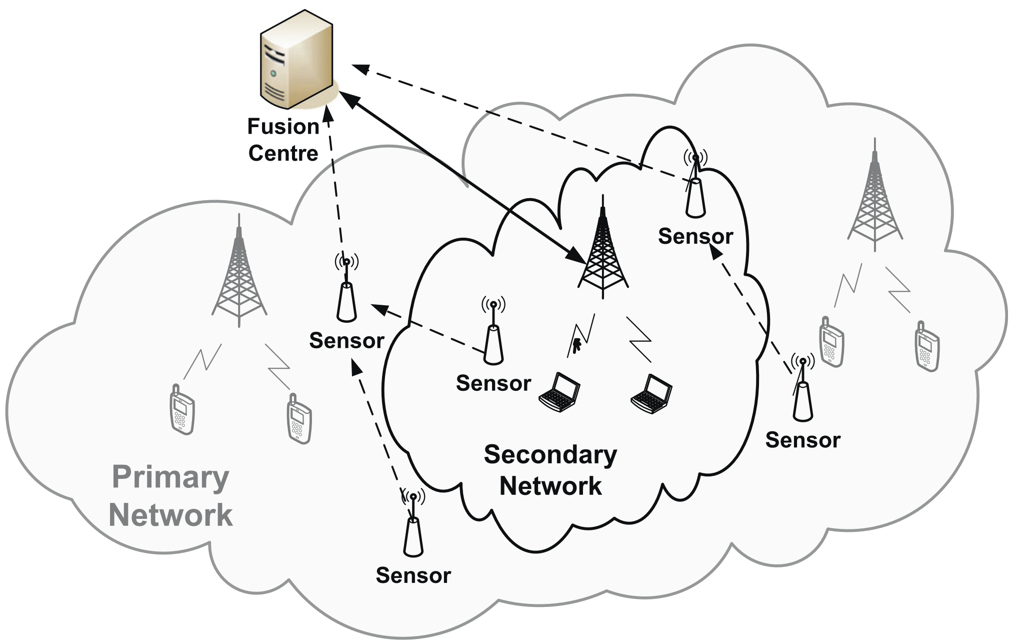


Fig. 1. General SENDORA scenario.

The CR system architecture depicted in Fig. 1 consists of three parts: the (secondary) communication architecture, the sensing architecture (sensors) and the fusion centre, which connects the communication and sensing architecture.

The fusion centre is a functional entity that receives sensing data collected through the WSN and estimates the spectrum usage situation in the area covered by the WSN. The fusion centre also communicates with the communication network providing it with the information it needs to operate cognitively in an optimal way.

In this study, the CR communication architecture will consist of a LTE network, cognitive femtocells and user terminals.

The sensing architecture consists of a fixed network of sensors complemented with sensing capabilities integrated in the cognitive femtocells and some of the terminals. The number and positions of the terminals will be random variables such that a WSN formed by terminals cannot guarantee detection confidence. A fixed deployed WSN also has the advantage that the sensors can communicate with each other and eventually with the fusion centre through a wired backbone network. Sensors can be powered from the mains. On the other hand, sensing integrated in the terminals will be co-located with the CRs and hence be capable of providing accurate local information to better protect primary users located close to the terminal.

3. Business case overview

Gradually, it can be seen that data volumes increase such that mobile networks are more frequently becoming capacity limited rather than coverage limited. A study in Ofcom (2011) for instance concludes that current 4G networks will not be able to meet the increase in capacity demand in the majority of traffic forecasts by year 2018 by spectrum efficiency improvements alone. The way operators usually solve this is by deploying more BSs and hence reduce cell size. In urban areas the cell sizes are already quite small and tend to become even smaller. There are two main challenges for the operator related to this: (i) the process of establishing a new BS site is expensive and challenging due to, for example, leasing agreement negotiations and regulation, construction and environmental constraints and (ii) it might be difficult to provide backhaul to the BSs.

The main idea behind the business case study is to compare two different strategies for upgrading the capacity of a capacity limited LTE network: the cognitive femtocell strategy and the combined conventional femtocell and new BS strategy.

3.1. *Cognitive femtocell strategy*

The first strategy, the cognitive femtocell (CogFem) strategy, is that a mobile operator offloads its LTE network by deploying cognitive femtocells using the SENDORA concept. This strategy turns the cognitive femtocell into a picocell and shifts some of the spectrum costs for offloading away from the operator. This strategy also addresses the challenges (i) and (ii) mentioned above. For challenge (i) the cognitive femtocell is deployed in the users home or office and for challenge (ii) the users broadband connection is used to provide backhaul to the cognitive femtocells. The cognitive femtocell also has the advantage over the conventional picocell that there might be a high potential to utilize frequencies other than the mobile network with wider bandwidths. A challenge with this strategy is that the operator has no power backups or alternative routes for the cognitive femtocell.

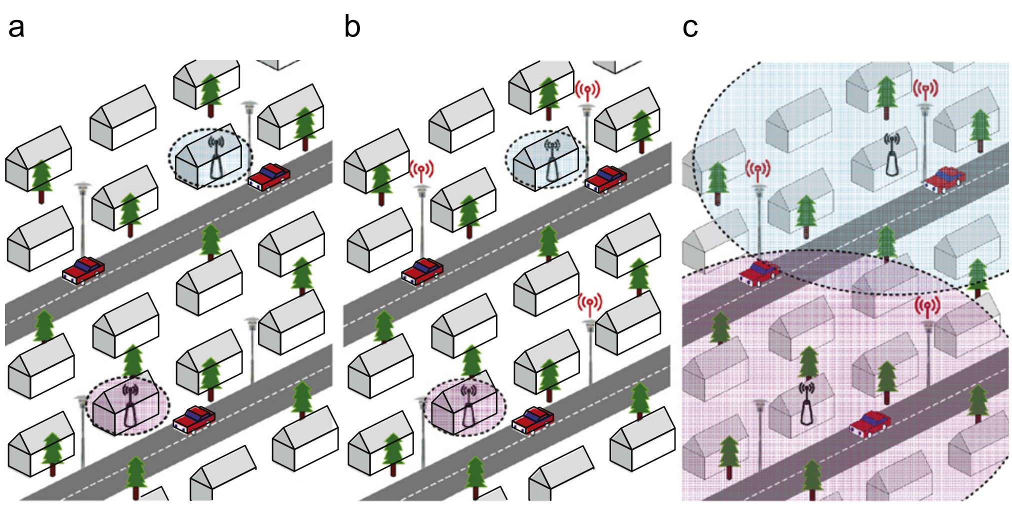


Fig. 2. Illustration of deployment strategy: (a) phase I, (b) and (c) phase II. (a) Deploy Cognitive Femtocells, (b) Deploy Sensors and (c) Increase Power.

The business case will follow a two-phased process of deployment as illustrated in Fig. 2:

Phase I In the first phase users will deploy femtocells within their homes and offices, possibly encouraged by incentives from the operator (e.g. subsidize femtocells, free calls). Some of these will be cognitive femtocells and the rest conventional femtocells. The operator will influence how cognitive femtocells are deployed in a way that optimizes coverage and capacity by approaching the owners of particular houses or buildings and offer them something in return for deploying a cognitive femtocell. The actual number of femtocells will depend on the forecasted traffic demand. An example scenario is illustrated in Fig. 2(a), where cognitive femtocells are deployed in two buildings providing indoor coverage. The cognitive functionality in the cognitive femtocell includes spectrum sensing and the ability to communicate over different frequencies opportunistically. Initially, since the cognitive femtocell cannot reliably detect primary usage of spectrum outside the building, the cognitive femtocell will use low transmit power and only cover the building indoors.

Phase II In the second phase the operator will enable the cognitive functionality and sensing in the cognitive femtocells and deploy fixed sensors. This will be done for a subset of the deployed cognitive femtocells dependent on offloading demand in the network. For the example scenario, Fig. 2(b) illustrates that fixed sensors are deployed in three lamp posts. The cognitive femtocells will then be able to increase transmit power in the frequency bands detected as unused within a certain range to cover areas outside the building. As a result, the cognitive femtocell is turned into a picocell able to offload the mobile network more than the conventional femtocell. Fig. 2(c) illustrates that the two cognitive femtocells have increased their transmit power to provide outdoor coverage.

In the case that there are no available frequencies for use, the cognitive femtocell can switch to the frequency used by the mobile network. The WSN can still be used to optimize cognitive femtocell coverage in the mobile operators band.

3.2. Conventional femtocell/new base station strategy

In this strategy, referred to as the conventional or regular femtocell (RegFem) strategy, the mobile operator deploys conventional femtocells to offload the LTE network. The conventional femtocells will only support the users that own the femtocell (2 users in average) and might not offload the macro network sufficiently, hence if required the operator will have to deploy additional macro BSs to meet the traffic demands.

It is noted that there exists a range of strategies that could be considered with combinations of macro, micro, pico and femto-cells and that the RegFem strategy can be considered as one of the worst case strategies for the operator. In real strategies there will more likely be a mixture of different cell sizes.

4. Business case inputs and assumptions

4.1. General assumptions

4.1.1. Overview of business case calculations

A cost flow analysis, which shows the amount of costs used by a company over a time period, will be used to get an indication of the profitability for the two strategies. Since the same service is offered in both strategies and it is assumed that the quality (e.g. coverage and capacity) is the same, the number of subscribers and hence the revenues will be identical. Therefore, the comparison of the two strategies can be done by only considering the costs for the capacity upgrades required to offload the network. There are many challenges related to revenue with femtocells such as the pricing plan used (e.g. free calls, unlimited data usage, better coverage) that also are important for the customers motivation to install the femtocell. Another effect from femtocells is churn reduction. The impact of these will be left for further work.

The costs consist of capital expenditures (CAPEX), often referred to as investments, and the operational expenditures (OPEX). When evaluating the cost flow the net present value (NPV)[1] will be used. The discount rate[2] used in the cost flow analysis is 10%. Due to large uncertainties in the assumptions for the future project timeline and the immature technology used, the cost flow analysis will be enhanced with sensitivity analysis.

4.1.2. Area covered and project timeline

The business case is calculated for a hypothetical Western European city with 1 million inhabitants and with an area of 200 km^2. The city has a downtown area of 50 km^2 and a suburban area of 150 km^2. In all, 50% of the subscribers are located in the downtown and 50% in the suburbs. The studied city is assumed to have a well-developed telecommunication market with a high penetration of both mobile and fixed telecommunication services such that a working competition environment with several network owners and service providers is assumed.

The business case study period is assumed to start in 2017 and end in 2022. In 2017, the cognitive femtocells and sensors can be expected to be developed and ready for commercial deployment. Cognitive femtocells and band aggregation might also be part of the LTE standard.

4.1.3. Network scenario, traffic forecasts and number of subscribers

A network scenario considered to be realistic will be described in the following. However, note that different network scenarios and traffic forecasts could be used that would give different results. Therefore, the most important results of this study are the sensitivity analysis of critical parameters.

The number of subscribers at the end of each year (eoy) is given in Table 1 corresponding to the underlying assumption that mobile broadband penetration is 90% and that the operator has 30% market share in 2022. It is assumed that the number of subscribers as a function of time follows an *S*-curve.

The average spectral efficiency in typical LTE networks is assumed to be 1.3 bits/Hz/cell[3] (Ofcom, 2011). It is assumed that the operator has 20 MHz of spectrum and builds BS cells with three sectors with frequency reuse one. This results in an average capacity of 78 Mbps per BS cell. For the BS[4] capacity, it is assumed that 400 active users can be supported.

It is assumed that the operator in 2017 has deployed LTE BSs in a hexagonal tiling pattern with an Inter Site Distance (ISD) of 500 m in the downtown and 1 km in the suburbs. The number of macro BSs deployed in the city in 2017 is then 404, with 231 in the downtown and 173 in the suburbs.

To estimate the need for capacity upgrades in the LTE network and traffic in busy hour (BH), the formula in Morgan (2008)[5] is used which is considered to be sufficient for long term capacity planning and business case calculations.

Assumptions for traffic demand in the years 2017–2022 and for the LTE macro network are given in Table 1. The BH traffic per month is calculated with a BH share of 15%. Traffic forecast assumption is done in two steps. First, an estimate of 4.65 GB/subscriber/month in 2016 is used from UMTS Forum (2011). Second, to find the growth from 2017 to 2022, the percentage growth in data traffic from 2015 to 2022 from the middle estimates in Ofcom (2011, Figure D21) as estimated by PA Consulting Group (2009) is used.

The three bottom rows in Table 1 give the number of BSs deployed, the traffic in BH and utilization per BS in each year without upgrading the network. The network reaches congestion in 2020.

4.1.4. Summary of parameter values used in the base case

The parameter values assumed in the base cases are listed in Table 2 and the two final columns identifies which strategy the parameter value is used in. Note that the prediction of these values is challenging due to the difference from today (2012) and the year 2017.

[1] NPV is the sum of a series of cash flows (revenues subtracted by costs) when discounted to the present value: $NPV=\sum_{t=1}^{n} A_t/(1+p)^t$, where p is the annual discount rate, A_t is the payment in year t and n is the project lifetime. NPV is the most important criteria when defining the profitability of the project and can be used for cost only.

[2] Discount rate is the rate used for discounting amounts to other points in time as in the calculation of NPV.

[3] Average spectral efficiency is based on signal-to-interference and noise ratio distribution in the cell, and will therefore not reflect the peak data rates in LTE.

[4] Throughout this paper a BS refers to a BS cell, not a BS sector.

[5] This formula can be stated as $V_M=k*(C*r*U)/f$, where V_M is the served capacity in Gigabyte (GB) per month, $k=13.5$ is a constant that converts from Mbps to GB/month, S is the number of sectors, C is the bandwidth in MHz, r is the average spectral efficiency, U is the utilization factor and f is the share of daily traffic that occurs during BH. $f=15\%$ will be used.

Table 1
Assumptions for network scenario.

Year	2017	2018	2019	2020	2021	2022
# Customers (eoy) (1000)	200	216	232	246	259	270
Traffic/customer/month (GB)	7.10	8.63	10.34	12.18	14.19	16.40
# Macro BSs	404	404	404	404	404	404
Traffic/BS in BH (Mbps)	39.0	51.3	65.9	82.3	101.0	121.8
Utilization/BS cell in BH (%)	50.1	65.8	84.5	105.5	129.4	156.1

Table 2
Parameter values used in the base case.

Parameter	Value (€)	Reduction (%)	CogFem	RegFem
CAPEX (per unit)				
BS price	5000	−10		X
BS site establishment	60 000	0		X
Conventional femtocell	100	−10	X	X
Cognitive femtocell	400	−10	X	
Femtocell installation	100	−2	X	
Femtocell gateway (GW)	500 000	−10	X	X
Femtocell OMS	100 000	−10	X	X
GW and OMS installation	100 000	−2	X	X
Sensor	300	−10	X	
Sensor installation	200	−2	X	
Fusion centre	150 000	−10	X	
Fusion centre installation	10 000	−10	X	
OPEX (per month)				
BS OPEX/month	1000	−2		X
Fixed sensor OPEX/month	15	−2	X	
Backhaul/month for femtocell	50	−2	X	

Table 3
Network data for the RegFem strategy.

Year	2017	2018	2019	2020	2021	2022
# Conv. femtocells	2001	4329	6953	9834	12 930	16 201
# Macro BSs deployed	404	404	404	462	555	654
Traffic/BS in BH (Mbps)	38.3	49.3	61.9	66.2	66.1	66.2
Utilization/BS cell (%)	49.0	63.2	79.4	84.9	84.8	84.9

4.2. *Conventional femtocell strategy related assumptions*

4.2.1. *Number of base stations and conventional femtocells*

It is assumed that the femtocell penetration is 1% in 2017 increasing with 1% each year to 6% in 2022. Furthermore, it is assumed that 57.2% of the femtocells are deployed in the downtown and 42.8% in the suburbs according to the traffic demand. A conventional femtocell installed in a household is able to offload between 4 and 8 users, but it is assumed that two subscribers are offloaded on average (Signals Research Group, 2009). The number of conventional femtocells deployed is given in Table 3.

The number of BSs required to support the capacity demand after offloading from the conventional femtocells (second row in Table 3) was estimated by the (Morgan, 2008) formula with the requirement that maximum BS utilization is 85% during BH. Note that offloading gain by the conventional femtocells are included when finding the number of required BSs. Average traffic per BS in BH and the final utilization per BS after offloading are given in the bottom rows.

The new macro BSs are placed in between the existing BSs giving a new grid for the BS sites with twice the density of the original grid, giving a new ISD of 354 m in downtown and 707 m in the suburbs. The coverage area of each BS in the new grid will be half of that in the original grid. The new BSs are placed in areas with high traffic demand and will offload their neighboring BSs.

4.2.2. *CAPEX for the conventional femtocell strategy*

The operator will subsidize the conventional femtocell with a price of 100 € in 2017 reducing to 47.8 € in 2022. The conventional femtocell is assumed to support a plug-and-play setup procedure with auto-configuration of parameters such as channel and transmit powers. The customers will install the femtocell themselves; hence, no installation costs are assumed which is in contrast to the cells in the mobile network.

CAPEX for the femtocell gateway, operation and management system (OMS), BS and establishment of a new BS site are given in Table 2.

4.2.3. OPEX for the conventional femtocell strategy

Costs associated with renting the backhaul capacity and maintaining the BS is 1000 €/month in 2017. The operator will subsidize backhaul for the conventional femtocell.

The conventional femtocell will be managed remotely by the OMS. If the conventional femtocell goes down and connectivity to the OMS is lost, then the customer is asked to return the conventional femtocell and a new one is sent to the customer.

The general OPEX is one of the major costs for a mobile operator. However, the general OPEX will not be considered since it is general for the total operations (e.g. customer acquisition, invoicing) and not specific to the RegFem strategy.

4.3. Cognitive femtocell strategy related assumptions

4.3.1. Number of cognitive femtocells

It is assumed that the range of a cognitive femtocell is 75 m in the downtown and 100 m in the suburbs. This is a reasonable number taking into account that it will use a low power transmitter and be located indoors. This range also ensures that spectrum holes can be well utilized (Grønsund & Grøndalen, 2011).

It is assumed that a set of cognitive femtocells will give the same offloading of the LTE network as the new macro BS in the RegFem strategy if they collectively have the same capacity and coverage area of at least the same size.

It is assumed that a cognitive femtocell supports 20 users, hence, 20 cognitive femtocells are required to support the same number of active users as a new macro BS.

The number of macro BSs and conventional femtocells deployed are given in the first row in Table 4. The third row gives the number of cognitive femtocells required to offload the macro network after offloading from the conventional femtocells is considered. In 2022 there will be 5000 cognitive femtocells, which will give the same capacity increase as the 250 new macro BSs in the RegFem strategy (Table 3).

A simulation study was performed to estimate the area covered by randomly located cognitive femtocells. Since the operator can influence where the femtocells are located, this will be a lower bound. The mean coverage as a function of the number of cognitive femtocells is shown in Fig. 3, which will be 43% with 5000 cognitive femtocells. As a comparison, 250 new macro BSs will give a coverage of 31%. Hence, the cognitive femtocells will collectively have the same capacity and larger coverage than the new macro BSs. This strongly indicates that the same services can be offered with both strategies.

Table 4
Network data for the CogFem strategy.

Year	2017	2018	2019	2020	2021	2022
# Macro BSs	404	404	404	404	404	404
# Conv. femtocells deployed	1168	2663	4454	6502	8765	11201
# Cog. femtocells required	0	0	0	1160	3020	5000
# Cog. femtocells deployed	833	1666	2499	3332	4165	5000
Traffic/BS cell in BH (Mbps)	38.3	49.3	61.9	66.2	66.1	66.2
Utilization/BS cell (%)	49.0	63.2	79.4	84.9	84.8	84.9

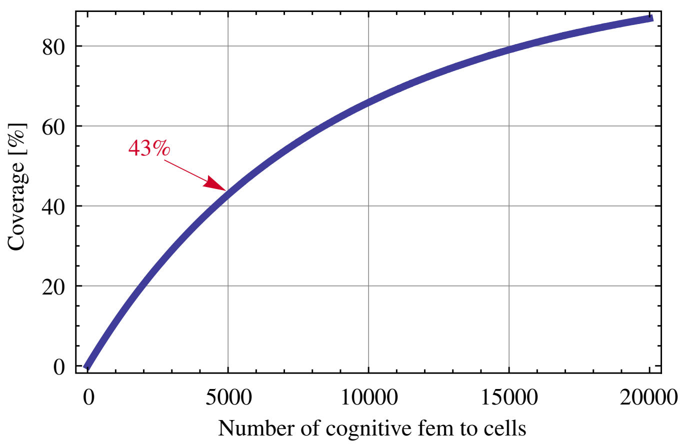


Fig. 3. Coverage provided by randomly located cognitive femtocells.

The operator deploys the cognitive femtocells equally distributed throughout the years to meet the requirement in 2022 as given in the fourth row. The cognitive femtocell density is assumed to be four times higher in the downtown than in the suburbs, hence, 57.2% and 42.8% of the femtocells are deployed in each area, respectively. This deployment is theoretical and might be difficult to achieve in reality with randomly deployed femtocells. Initially, the cognitive femtocells will operate as conventional femtocells. When a capacity upgrade is required in 2020, the cognitive functionality will be activated.

Average traffic in BH and utilization per macro BS after offloading by all femtocells are given in the two bottom rows.

4.3.2. Costs for purchasing and installing the cognitive femtocell

It is assumed that the operator will subsidize the cognitive femtocell. The femtocell is assumed to operate in TVWS, that is, in the frequency range from 470 to 790 MHz (van de Beek, Riihijarvi, Achtzehn, & Mahonen, 2011). Low complexity sensors are assumed (Kokkinen et al., 2010), for example based on the energy detection or autocorrelation based feature detection which have implementations requiring little chip area and low power consumption. The sensor receiver is assumed to have a sensitivity of -121 dBm in 200 kHz bandwidth as estimated in Kansanen et al. (2009) based on a survey of recently published relevant circuits. The sensing interval is assumed to be 10 ms, which makes it easier to achieve the targeted sensitivity with a low cost implementation. A quadrupling in price of the conventional femtocell is assumed because of the cognitive functionalities resulting in a purchase price of 400 € per cognitive femtocell in 2017.

The main difference from the conventional femtocell is the addition of sensing capabilities and the protocol to communicate with the fusion centre to find the optimal frequency. To optimize outdoor coverage, the cognitive femtocell will be installed by the operator assumed to cost 100 €.

To support the cognitive femtocells, the operator must purchase and install a femtocell gateway and a femtocell OMS with prices as given in Table 2.

4.3.3. Costs for cognitive femtocell backhaul

Backhaul is one of the main challenges for femtocell business cases. In this business case, the cognitive femtocell can be backhauled in two ways. In the first and preferred option an existing fixed broadband connection in the home or office will backhaul the cognitive femtocell. In the second option the LTE network will backhaul the cognitive femtocell, where an external antenna will be connected to the cognitive femtocell to provide an optimal transmission link to the BS. The downside of this option is that BS capacity will be used. This option will be used only if the first option does not exist and is assumed to be zero in the base case.

It is assumed that the backhaul could either be ADSL, cable or fibre. Furthermore, it is assumed that the operator takes the cost for using the subscribers fixed broadband connection as backhaul. A multiplexing gain of 1:20 is assumed which should amount to an experienced capacity assumed to be 20 Mbps/user. To estimate the broadband subscription costs, the average price of a broadband subscription in European countries with bitrate 20 Mbps is found to be about 30 €/month. Since the fixed broadband operator also uses a multiplexing rate an agreement between the mobile operator and the fixed broadband operator is assumed of 50 €/month in 2017, a 5 € reduction from today (2012) and a doubling in subscription fee.

4.3.4. OPEX for the cognitive femtocell strategy

OPEX for new BSs in the macro network (site leasing, maintenance) is avoided in the CogFem strategy. The cognitive femtocells will be managed remotely by the OMS. In situations where the cognitive femtocell goes down and connectivity to the OMS is lost, the customer is asked to return the cognitive femtocell and a new one is sent to the customer. As for the RegFem strategy, maintenance for the cognitive femtocell is assumed to be zero. General OPEX will not be considered.

4.3.5. Sensor network related assumptions

The WSN related assumptions consist of costs related to purchasing and operating the fixed sensor network and the fusion centre. Assumptions for CAPEX and OPEX related to the WSN are summarized in Table 2 and the reader is referred to Grøndalen et al. (2011) for details related to each parameter.

To determine the number of fixed sensors that will be deployed, it is necessary to find the required fixed sensor density (Fodor, Glaropoulos, & Pescosolido, 2009) which is one of the most important parameters for the WSN deployment. The fixed sensor density is assumed to be 65 sensors/km^2 as found in Grøndalen et al. (2011, Section V.C) based on the study in Pescosolido et al. (2010, Section 2).[6]

The total number of fixed sensors rolled out given in Table 5 depends on the total number of cognitive femtocells deployed and on the individual cognitive femtocell coverage area. Second, it depends on when the operator deploys the cognitive femtocells based on capacity demand.

[6] The required fixed density value represents the mean of the values for two cases with maximum interference probability requirements 10^{-6} and 10^{-3}, where the primary system is LTE.

Table 5
Number of fixed sensors deployed.

Year	2017	2018	2019	2020	2021	2022
# Fixed sensors downtown	0	0	0	98	256	391
# Fixed sensors suburbs	0	0	0	517	1346	2229
# Fixed sensors total	0	0	0	615	1602	2620

5. Business case evaluation

5.1. Cost comparison results

Total accumulated costs for the base cases of the CogFem and RegFem strategies are given in Fig. 4(a) with resulting NPV for costs 8.52 and 10.61 M€, respectively, so the CogFem strategy will be 2.09 M€ more profitable than the RegFem strategy in 2022 for the base case calculation.

From the yearly CAPEX and OPEX for the two strategies given in Fig. 4(b), it can be seen that OPEX for both strategies increases in 2020 when the network requires offloading. It can also be seen that CAPEX for the RegFem strategy increases especially in 2020 due to deployment of new BSs sites.

5.2. Sensitivity of backhaul costs for the cognitive femtocell

From the sensitivity of the monthly price for backhaul per cognitive femtocell in Fig. 5, it is observed that the costs for the two strategies equals when monthly price for backhauling the cognitive femtocell reaches 82 €, a 64% increase from the base case (50 €/month as pointed to by the arrow). It is concluded that the price for cognitive femtocell backhaul is a critical parameter and it will therefore be important to study this in more detail.

5.3. Sensitivity of femtocell offloading gain

Sensitivity of the number of users supported by the cognitive femtocell given in Fig. 6(a) shows that the CogFem NPV exceeds the RegFem NPV when the number of users supported reduces to 14, in which the number of cognitive femtocells and sensors deployed are 7.143 and 3.550, respectively. This is a critical parameter that should be considered when developing cognitive femtocells.

For the sensitivity of number of users offloaded by a conventional femtocell given in Fig. 6(b), it can be seen that the NPV equals when 5.5 users are offloaded in average.

5.4. Sensitivity of macro BS site establishment

From the sensitivity of the costs to establish a new BS site in Fig. 7, it can be seen that the costs for the RegFem strategy approach those of the CogFem strategy rapidly when costs reduce and that the NPV equals when costs reach 35 251€. If costs increase, it can be seen that the CogFem strategy will become increasingly more profitable than the RegFem strategy. It can be concluded that since BS site establishment is one of the major costs for the RegFem strategy, this is one of the areas where major costs are saved with the CogFem strategy. It will be important for the operator using the RegFem strategy to exploit site sharing when possible.

5.5. Sensitivity of cognitive femtocell subsidization

It was assumed that the operator subsidizes the cognitive femtocell and the price was difficult to estimate since the technology is immature. Fig. 8 illustrates that the sensitivity is moderate and that the NPV equals when the cognitive femtocell price is 1.053 € (163.25% increase).

5.6. Sensitivity of cognitive femtocell coverage

Sensitivity of the cognitive femtocell coverage radius in the downtown and suburbs is studied separately. It can be seen in Fig. 9(a) that the NPV increases when the coverage becomes very low. This is because the number of cognitive femtocells and related costs increases. An interesting observation is that the NPV increases especially when the cognitive femtocell radius is lower than the sensor radius. In this case, no senors will be deployed in the respective part of the city as illustrated for the downtown and suburbs separately in Fig. 9(b). However, the total number of cognitive femtocells deployed increases considerably as illustrated in Fig. 9(c).

Another interesting finding is that an optimal coverage range for the cognitive femtocells can be found for the lowest NPV, which is found to be between 40 and 70 m in the downtown and 80 m in the suburbs. The reason for the increase in

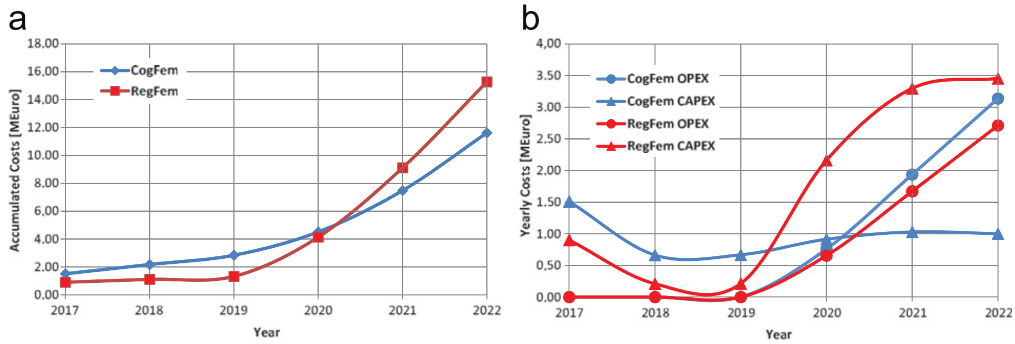


Fig. 4. Results for the base cases: (a) accumulated costs and (b) yearly CAPEX and OPEX.

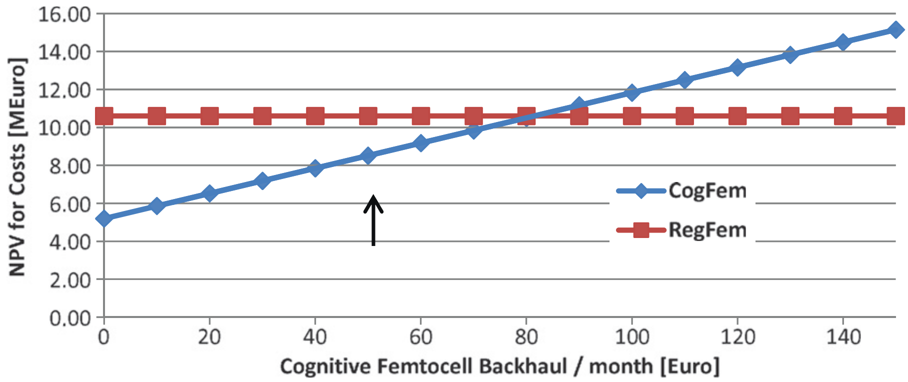


Fig. 5. Sensitivity analysis of the cognitive femtocell backhaul.

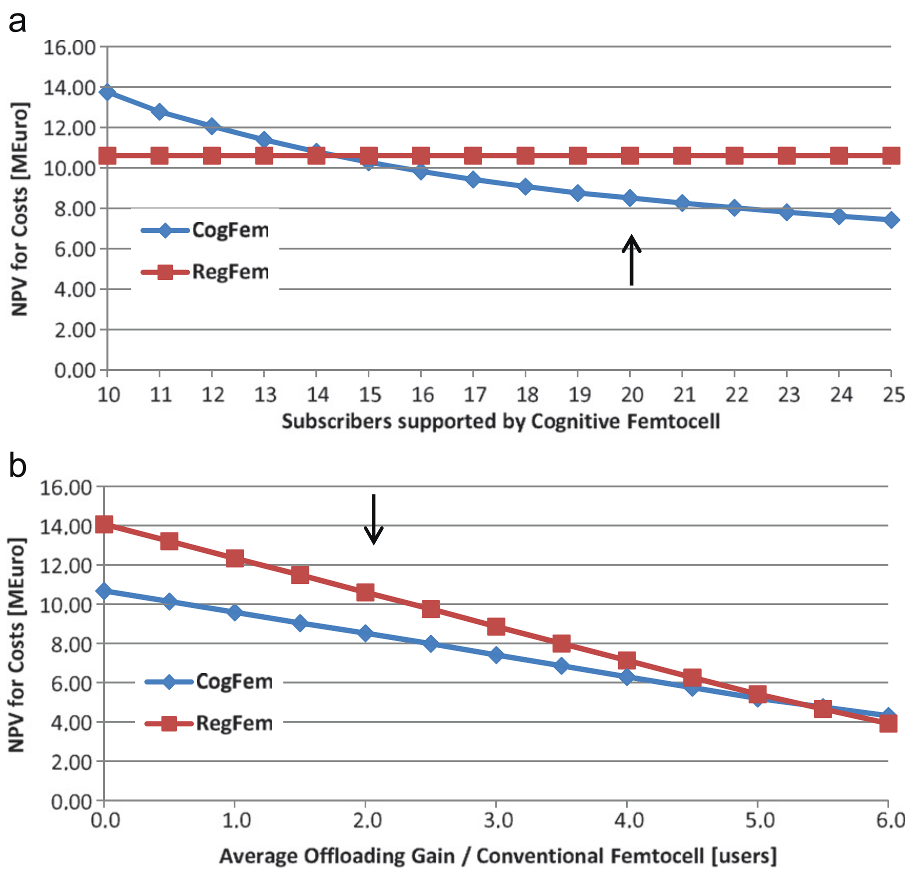


Fig. 6. Sensitivity analysis for the offloading gain: (a) subscribers supported per cognitive femtocell and (b) average offloading gain per conventional femtocell.

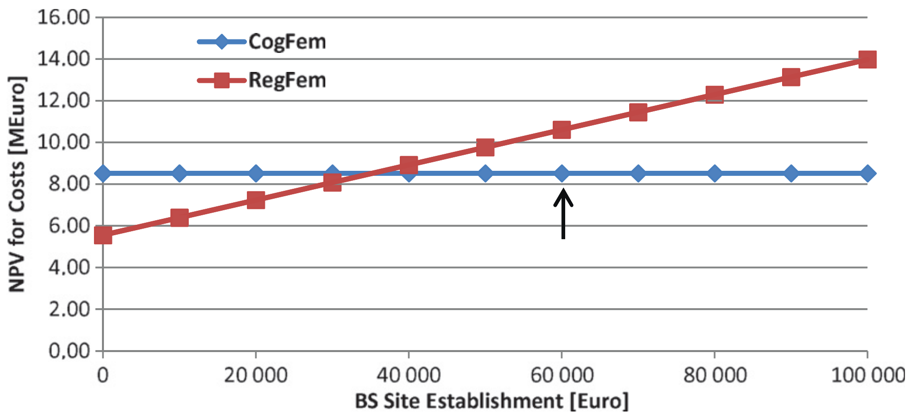


Fig. 7. Sensitivity analysis of the costs for BS site establishment.

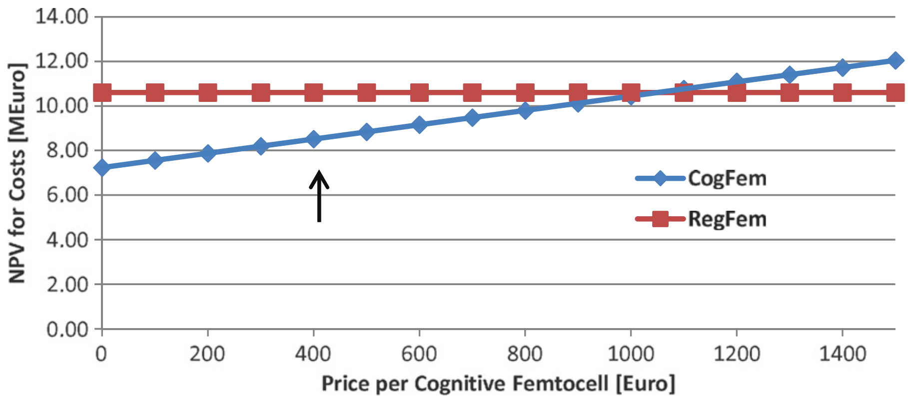


Fig. 8. Sensitivity analysis of the cognitive femtocell price.

NPV at higher distances is that the number of sensors increases while the number of cognitive femtocells remains constant due to the capacity requirement. The reason for the increase in the number of sensors is that more sensors are required for each cognitive femtocell. If these optimal values were selected for downtown and suburbs simultaneously, then NPV in the CogFem strategy would be 7.62 M€ resulting in 0.90 M€ lower costs compared to the base case. However, it should be noted that as the ranges reduces, the probability that 20 users are within the coverage range of a cognitive femtocell reduces.

5.7. *Sensitivity related to the fixed sensor network*

It is found that the sensitivity of the fixed sensor density and fixed sensor price given in Figs. 10(a) and (b), respectively, is than in Grøndalen et al. (2011). The reason is that sensing embedded in cognitive femtocells causes less sensors to be deployed. The NPV in the two strategies equals if the requirement for fixed sensor density reaches 104 senors/km^2. For the fixed sensor price sensitivity, the NPV equals at 2.117 €.

In an alternative strategy where the cognitive femtocell does not have an embedded sensor, the NPV in the CogFem strategy would be 9.80 M€ resulting in 0.81 M€ higher costs.

5.8. *Sensitivity of base station capacity*

From sensitivity on spectral efficiency in Fig. 11, it can be seen that the lower the spectral efficiency, the more profitable the CogFem strategy than the RegFem strategy. This is because the number of deployed BSs and cognitive femtocells increases considerably for the lower spectral efficiency. When spectral efficiency increases the need for offloading reduces, hence the RegFem strategy becomes more profitable.

5.9. *Sensitivity of population and customer density*

From sensitivity on the total population and number of customers in Fig. 12, it can be seen that the costs for the CogFem strategy increase less than for the RegFem strategy as the population and hence the number of customers increases.

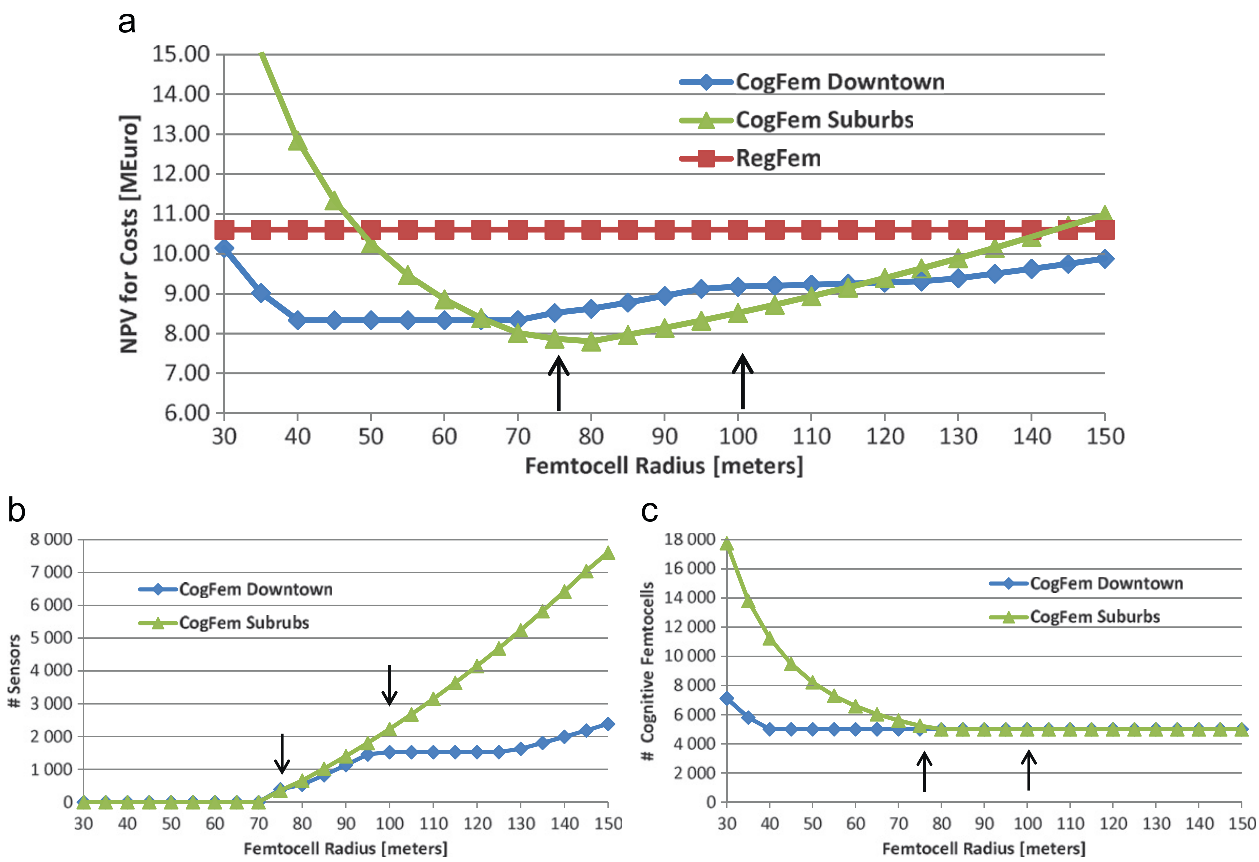


Fig. 9. Sensitivity analysis of the femtocell coverage radius in the downtown and suburbs separately: (a) NPV; (b) the number of sensors; and (c) the number of cognitive femtocells.

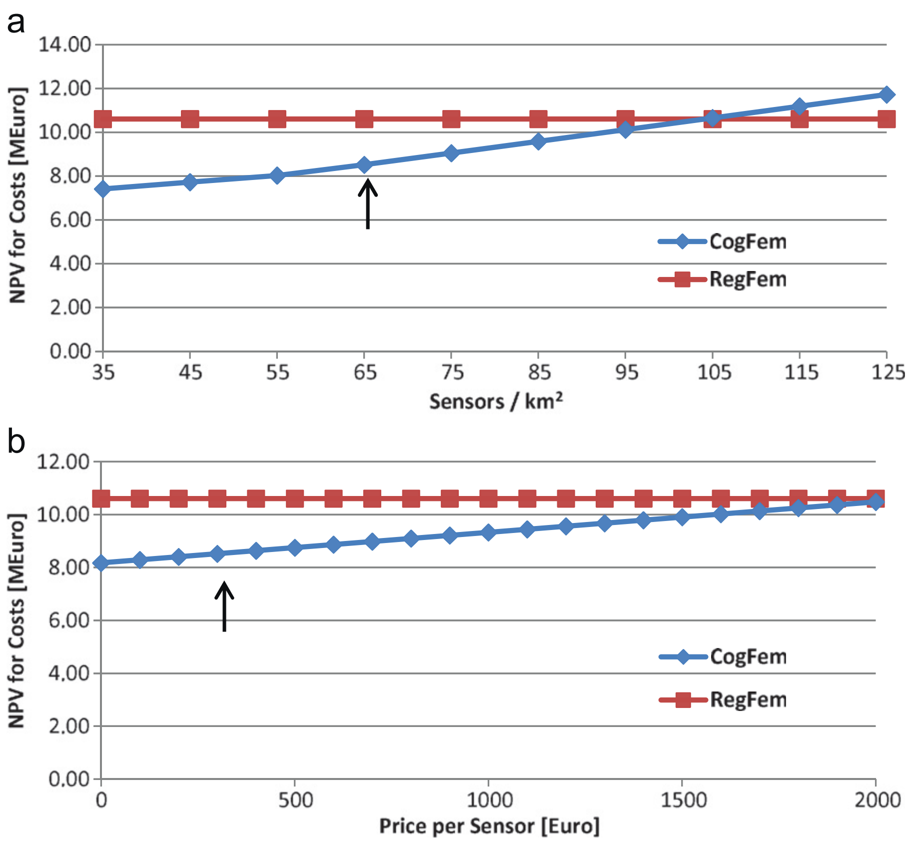


Fig. 10. Sensitivity analysis for the fixed sensor network: (a) fixed sensor density and (b) fixed sensor price.

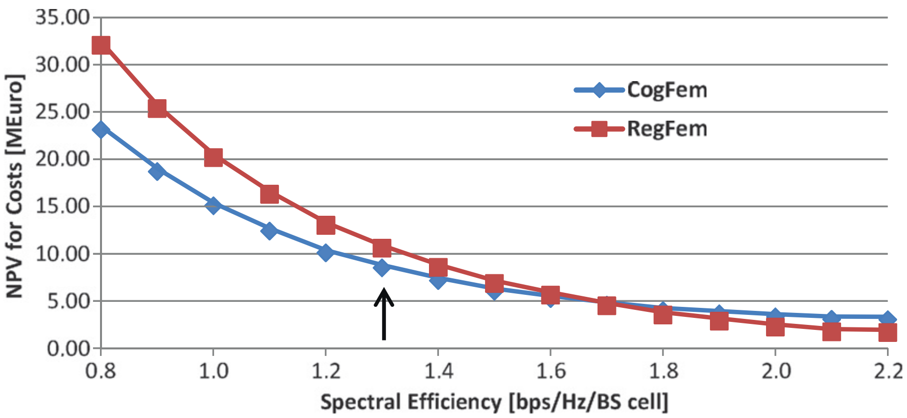


Fig. 11. Sensitivity analysis of the spectral efficiency for the macro BS.

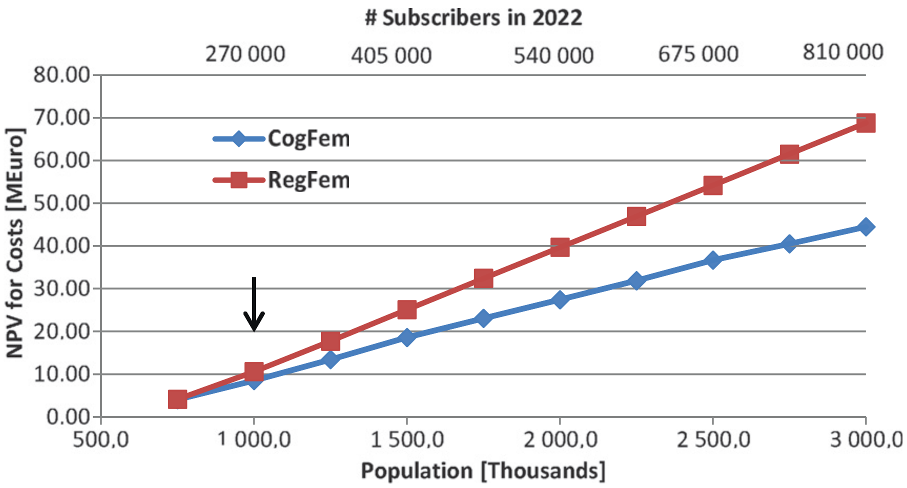


Fig. 12. Sensitivity analysis of the population and customer density.

6. Conclusions

This paper proposed and analyzed critical aspects of a business case where a mobile operator offloads its LTE network by deploying cognitive femtocells. When aided by a sensor network the cognitive femtocells are able to use frequencies other than the mobile network and hence increase its power to cover outdoor areas and neighbouring buildings. The cognitive femtocell (CogFem) strategy was compared with a strategy where the operator deploys conventional femtocells (RegFem) and additional new BSs to offload the macro network. By using cost flow analysis, it was found that the CogFem strategy can be more profitable than the RegFem strategy. The authors do not conclude that the studied concept is the most profitable since there exist numerous other strategies that could be compared. However, the authors note that it is challenging to estimate the costs related to the immature technology studied, so the main value of this study is to identify critical aspects related to the cognitive femtocell business case as an important contribution to future research and development.

It was found that one of the most critical parameters for the CogFem strategy is the price for backhauling the cognitive femtocell. Little information exists about this price, hence a more detailed study to estimate this price will be of highest importance.

It was found that the number of supported users by a cognitive femtocell is a critical parameter which is important to consider when developing cognitive femtocells.

The costs for establishing new BS sites are the major cost for the RegFem strategy which is omitted in the CogFem strategy. Hence, minimizing the number of new BS site establishments with site sharing will be important for the RegFem strategy to be comparable with the CogFem strategy.

It was also found that the coverage radius for the cognitive femtocell is important and the optimal radii were found to be between 40 and 70 m in the downtown and 80 m in the suburbs. Lower ranges caused more cognitive femtocells to be deployed resulting in much higher costs.

It was found that parameters related to the senor network such as required density, price and OPEX for the fixed sensors are less critical when sensors are embedded in the cognitive femtocells.

References

Chandrasekhar, V., Andrews, J., & Gatherer, A. (2008). Femtocell networks: A survey. *IEEE Communications Magazine*, *46*, 59–67.

Chapin, J., & Lehr, W. (2011). Mobile broadband growth, spectrum scarcity, and sustainable competition. In: *Proceedings of the Telecommunications policy research conference*. 〈http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1992423〉.

Choi, D., Monajemi, P., Kang, S., & Villasenor, J. (2008). Dealing with loud neighbors: The benefits and tradeoffs of adaptive femtocell access. In: *Proceedings of the IEEE global telecommunications conference* (*GLOBECOM*) (pp. 1–5). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4698315〉.

Claussen, H., Ho, L. T. W., & Samuel, L. G. (2008). An overview of the femtocell concept. *Bell Labs Technical Journal*, *13*(1), 221–245.

FCC. (2002). *Spectrum policy task force report*. Technical Report ET Docket No. 02-155. 〈http://wireless.fcc.gov/auctions/31/releases/fc020155.pdf〉.

FCC. (2008). *Second report and order and memorandum opinion and order*. Technical Report ET Docket No. 08-260. 〈http://www.fcc.gov/document/part-15-tv-bands-devices〉.

FCC. (2010). *Second memorandum opinion and order*. Technical Report ET Docket No. 10-174. 〈http://www.aes.org/sections/pnw/pnwrecaps/2007/whitespace_oct07/sept_23/memorandum_opinion_and_order.pdf〉.

Fodor, V., Glaropoulos, I., & Pescosolido, L. (2009). Detecting low-power primary signals via distributed sensing to support opportunistic spectrum access. In: *Proceedings of the IEEE international conference on communications* (*ICC*) (pp. 1–6). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5198909〉.

Grøndalen, O., Lähteenoja, M., & Grønsund, P. (2011). Evaluation of business cases for a cognitive radio network based on wireless sensor network. In: *IEEE symposium on new frontiers in dynamic spectrum access networks* (*DySPAN*) (pp. 242–253). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5936213〉.

Grønsund, P., & Grøndalen, O. (2011). Performance of a sensor network aided cognitive radio system. In: *IEEE 22nd international symposium on personal, indoor and mobile radio communications* (*PIMRC*) (pp. 629–634). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6140039〉.

Gür, G., Bayhan, S., & Alagöz, F. (2010). Cognitive femtocell networks: An overlay architecture for localized dynamic spectrum access [dynamic spectrum management]. *IEEE Wireless Communications*, *17*, 62–70.

Harjula, I., & Hekkala, A. (2011). Spectrum sensing in cognitive femto base stations using welch periodogram. In: *IEEE 22nd international symposium on personal indoor and mobile radio communications* (*PIMRC*) (pp. 2305 –2309). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6139930〉.

Kansanen, K., Fodor, V., Hayar, A., Presti, F. L., Ryynänen, J., Stadius, K. (2009). *Interference model based on scenarios and system requirements*. Technical Report. 〈http://www.sendora.eu/node/125〉.

Kawade, S., & Nekovee, M. (2011). Broadband wireless delivery using an inside-out tv white space network architecture. In: *Proceedings of the IEEE global telecommunications conference* (*GLOBECOM*) (pp. 1–6). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6134346〉.

Kokkinen, K., Kosunen, M., Chaudhari, S., Koivunen, V., Ryynänen, J., Danev, D. (2010). *Test report on sensing algorithm implementation*. Technical Report. 〈http://www.sendora.eu/node/218〉.

Mercier, B., Fodor, V., Thobaben, R., Skoglund, M., Koivunen, V., Lindfors, S. (2009). Sensor networks for cognitive radio: Theory and system design. In: *ICT mobile summit*. 〈http://www.sendora.eu/system/files/ICTMobileSummit_SENDORA_Paper.pdf〉.

Morgan, J. P. (2008). *The power of mobile broadband*. Technical Report. 〈http://www.jpmorgan.com/〉.

Ofcom. (2009). *Digital dividend*: *Cognitive access*, *statement n licence-exempting cognitive devices using interleaved spectrum*. Technical Report. 〈http://stakeholders.ofcom.org.uk/consultations/cognitive/statement/〉.

Ofcom. (2011). *4G capacity gains*. Technical Report. 〈http://stakeholders.ofcom.org.uk/market-data-research/other/technology-research/2011/4G-Capacity-Gains/〉.

PA Consulting Group. (2009). *Predicting areas of spectrum shortage*. Technical Report. 〈http://stakeholders.ofcom.org.uk/market-data-research/other/technology-research/research/future-spectrum/predicting/〉.

Pawelczak, P., Nolan, K., Doyle, L., Oh, S. W., & Cabric, D. (2011). Cognitive radio: Ten years of experimentation and development. *IEEE Communications Magazine*, *49*, 90–100.

Pescosolido, L., Petrioli, C., Cammarano, A., Barbarossa, S., Bongivanni, C., Fodor, V. (2010). *Report on cross-layer protocol stack design*. Technical Report. 〈http://www.sendora.eu/node/222〉.

Riihijarvi, J., Nasreddine, J., & Mahonen, P. (2011). Influence of primary network structure and dynamics on achievable performance of cognitive wireless networks. In: *IEEE symposium on new frontiers in dynamic spectrum access networks* (*DySPAN*) (pp. 359–370). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5936225〉.

Signals Research Group. (2009). *Femto forum business case white paper*. White Paper. 〈http://www.smallcellforum.org/resources-white-papers〉.

Tandra, R., Sahai, A., & Mishra, S. (2009). What is a spectrum hole and what does it take to recognize one. *Proceedings of the IEEE*, *97*, 824–848.

UMTS Forum. (2011). *Mobile traffic forecasts 2010–2020*. Technical Report. 〈http://www.umts-forum.org/component/option,com_docman/task,cat_view/gid,485/Itemid,213/〉.

van de Beek, J., Riihijarvi, J., Achtzehn, A., & Mahonen, P. (2011). Uhf white space in europe: A quantitative study into the potential of the 470–790 MHz band. In: *IEEE symposium on new frontiers in dynamic spectrum access networks* (*DySPAN*) (pp. 1–9). 〈http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5936207〉.

Wang, J., Ghosh, M., & Challapali, K. (2011). Emerging cognitive radio applications: A survey. *IEEE Communications Magazine*, *49*, 74–81.

Weiss, M. B., Altamimi, M., & Cui, L. (2012). Spatio-temporal spectrum modeling: Taxonomy and economic evaluation of context acquisition. *Telecommunications Policy*, *36*, 335–348.

Weitzen, J., & Grosch, T. (2010). Comparing coverage quality for femtocell and macrocell broadband data services. *IEEE Communications Magazine*, *48*, 40–44.

Xiang, J., Zhang, Y., Skeie, T., & Xie, L. (2010). Downlink spectrum sharing for cognitive radio femtocell networks. *IEEE Systems Journal*, *4*, 524–534.

Yucek, T., & Arslan, H. (2009). A survey of spectrum sensing algorithms for cognitive radio applications. *IEEE Communications Surveys Tutorials*, *11*, 116–130.

Zhao, Q., & Sadler, B. M. (2007). A survey of dynamic spectrum access. *IEEE Signal Processing Magazine*, *24*, 79–89.

Paper F
System Level Performance of IEEE 802.22 with Sensing-Based Detection of Wireless Microphones

Pål Grønsund, Przemysław Pawełczak, Jihoon Park and Danijela Čabrić

Accepted for publication in IEEE Communications Magazine, 2013.

System Level Performance of IEEE 802.22-2011 with Sensing-Based Detection of Wireless Microphones

Pål Grønsund, Przemyslaw Pawelczak, Jihoon Park, and Danijela Cabric

***Abstract*—We present the state-of-the-art system level evaluation of the IEEE 802.22-2011 standard using a highly detailed simulator implementation in NS-2. In the evaluation our attention is focused on the effect of spatiotemporal wireless microphone (WM) activity on the performance of the IEEE 802.22-2011 network, while considering novel spectrum sensing strategies and multimedia traffic with different prioritization in IEEE 802.22-2011. Our general finding is that the IEEE 802.22-2011 standard deals well with WMs and prioritization of simultaneous multimedia traffic using different QoS profiles, while some surprising conclusions follow.**

I. Introduction

The IEEE 802.22-2011 [1] standard is the first and most sophisticated standard for operation in TV white spaces. An IEEE 802.22-2011 system can use sensing techniques to detect sudden appearance of primary users (PUs) of the TV bands such as TV transmitters and Wireless Microphones (WMs). The TV broadcasters update the database about their frequency usage and transmit power levels at all locations. Other low power devices operating in these bands such as WMs might update the database, but might also appear suddenly at random locations without notification. Thus, detection and protection of these WMs are considered as one of the greatest challenges for the IEEE 802.22-2011 system. An alternative approach by regulators is to allocate "safe harbor" channels, which can be used by the WMs without registering in the database. However, spectrum sensing could still be used to increase spectrum utilization significantly in these channels. It is also an open question what different regulators will actually do to protect WMs.

Unfortunately, since the initiation of the IEEE 802.22-2011 standard in 2004, to the best of our knowledge, except of [2], [3], [4], [5], there exist no real life field trials nor any comprehensive system level studies with the complete IEEE 802.22-2011 implementation. Moreover, there exist no performance evaluations of the complete system protocol stack of the IEEE 802.22-2011 standard considering (WM) sensing. Therefore, in order to study the system wide performance of IEEE 802.22-2011, we have developed the most complete and up to date implementation of the IEEE 802.22-2011 stack in the NS-2 simulator, which was introduced first in [2], [3], [4], [5].

In this article, we first evaluate the IEEE 802.22-2011 performance for simultaneous multimedia traffic with different QoS profiles considering broad set of single and two-stage sensing strategies. Then we look into the instantaneous impact of IEEE 802.22-2011 network on the WMs.

Pål Grønsund is with Telenor, Snarøyveien 30, 1331 Fornebu, Norway; Simula Research Laboratory, Martin Linges Vei 17, 1364 Fornebu, Norway; and the Department of Informatics, University of Oslo, Gaustadallen 23, 0373 Oslo, Norway (email: paalrgr@ifi.uio.no).

Przemyslaw Pawelczak is with the Department of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands (email: p.pawelczak@tudelft.nl).

Jihoon Park is with Samsung Information Systems, 2820 Orchard Parkway, San Jose, CA 95120, USA (email: jpark0@samsung.com).

Danijela Cabric is with the Department of Electrical Engineering, University of California, Los Angeles, 56-125B Engineering IV Building, Los Angeles, CA 90095-1594, USA (email: danijela@ee.ucla.edu).

II. Modeling Complete IEEE 802.22-2011

For the ease of exposition, in this section we recall and recapitulate much of the description of the IEEE 802.22-2011 network model presented simultaneously in [2], [3], [4], [5], but with the important extension of multimedia traffic and different QoS profiles.

A. Network Model

We consider an IEEE 802.22-2011 system limited to one Base Station (BS) and a set of Customer Premises Equipment (CPEs). The CPEs are fixed at certain locations, in accordance with the IEEE 802.22-2011 standard. The distance between the BS and CPE and the distance between the BS and WM will be set to a fixed value in some scenarios and randomly selected in other scenarios. The simulator supports all channels in the UHF band, but a subset of channels are selected for operation in the studied scenarios (i.e. four channels at frequencies denoted F1–F4). A personal computer connected via Ethernet to the BS will establish links to the CPEs and run different traffic models.

In this study we focus only on WMs as an example of PUs, assuming that in the coverage area of the IEEE 802.22-2011 BS no active TV transmissions are present, since these are assumed to be known through the database. In this evaluation we assume that WM activity will be detected only by sensing techniques with no support from beacon protocol like IEEE 802.22.1 [6]. We emphasize that spectrum sensing is still a fundamental WM detection method as some of the recent proposals by the US Federal Communications Commission, allocating two separate frequency bands for WM operation only [7], will limit the spectral efficiency of the available white spaces. Also, existing unlicensed WMs will continue to exist in other UHF bands for many years.

B. Traffic Model

1) IEEE 802.22-2011 Traffic Model: Three different traffic models are used for the IEEE 802.22-2011 network in the simulations scenarios, variable bit rate (VBR), video and VoIP, as summarized in Table I. The VoIP and video traffic models are similar to the models used in [8] when evaluating performance of IEEE 802.16e. VoIP is modeled as an ON/OFF traffic source with voice activity detection where packets are only generated during ON periods. The given ON and OFF durations are average and assumed to be exponentially distributed [9]. Video traffic uses a real life pre-encoded MPEG4 trace [10]. VBR traffic will run over UDP and will be used to measure maximum IEEE 802.22-2011 system throughput. Maximum traffic rates will then be simulated by constantly transmitting UDP packets with bit rates higher than the channel capacity to fully load the buffers.

Two QoS profiles are implemented: unsolicited grant service (UGS) and best effort (BE). In detail, UGS sets the guaranteed interval between packets and the packet size, and it has priority over BE. The BE QoS profile is used for VBR and video traffic, while the UGS QoS profile is used for VoIP traffic.

2) Wireless Microphone Traffic Model: When the WM becomes active, its traffic pattern is characterized by a 100% duty cycle until the WM disappears. It should be noted that NS-2 is packet transmission-based, hence we assume that WM virtually transmits data packets consecutively during the whole IEEE 802.22-2011 OFDMA frame in order to simulate the 100% duty cycle traffic pattern.

We are not aware of any work that give statistics on WM traffic distribution, hence we assume that all WMs generate new connections according to the negative exponential distribution [11]. The average inter-arrival time and the average occupancy time (both exponentially distributed) are denoted, respectively, as $1/\lambda_w$ and $1/\mu_w$. The WMs operate in the UHF band and are configured with transmit power of 200 mW. More discussion on the impact of the temporal activity of WMs on the IEEE 802.22 network can be found in [2].

III. Features of IEEE 802.22-2011: Standard versus Implementation

As in the case of previous section, for the ease of reference, we recall much of the information on the simulator features presented also in [2], [3], [4], [5], but with modifications to the spectrum sensing strategies and parameter settings in the simulator.

The IEEE 802.22-2011 is very similar to the IEEE 802.16e standard, hence we adapt an extensive implementation of the IEEE 802.16e standard in NS-2 [12] developed for the WiMAX Forum to represent IEEE 802.22-2011 as specified by the standard [1]. The features that are different from IEEE 802.16 are implemented and conform to the best extent to the functional requirements as specified in the IEEE 802.22-2011 standard.

The most relevant parameters for the two systems, IEEE 802.22-2011 and IEEE 802.16e, were compared in [13], [5]. This comparison is extended in Table II, together with information on the set of protocol profiles implemented in NS-2. In the subsequent sections we present the IEEE 802.22-2011 system and simulation model with main focus on the spectrum management and sensing functions implemented, but also on the general changes to the IEEE 802.16e physical layer.

A. OFDMA and Channelization Structure

Both the IEEE 802.22-2011 downlink and uplink subframes have totally 60 subchannels, where each subchannel consists of 28 subcarriers out of which 24 data and 4 pilot subcarriers. The IEEE 802.22-2011 network can operate on any vacant TV channel if it is not used by the PU (in our case WM). Channel bonding of scattered available channels is not considered in this study. A WM occupies only one channel. Fractional frequency usage where some subcarriers occupied by WMs in one frequency band are notched out and the remaining are utilized by IEEE 802.22-2011, will not be considered.

In our IEEE 802.22-2011 NS-2 implementation only the 6 MHz profile is used. A subset of typical channels in the UHF band are selected for operation in the simulation model, the four channels in the range 31 to 34 corresponding to the center frequency of 575, 581, 587 and 593 MHz, respectively. For the subcarrier allocation strategy, partially used subcarrier (PUSC) allocation is used in our NS-2 implementation. Guard bands are considered at both ends of the channel bandwidths with a total of 368 guard and null subcarriers.

The transmit/receive transition gap (TTG) is set to 210 μs, which supports a 30 km distance between BS and CPE. The receive/transmit transition gap (RTG) is set to 81.8 μs. There are totally 26 symbols, each of 373.33 μs duration, where the DL:UL ratio is set to 2:1.

B. OFDMA Traffic Scheduling

The MAC layer of IEEE 802.22-2011 uses linear scheduling to allocate OFDMA slots to traffic from the upper layers in both the downlink and uplink subframes, as opposed to a rectangular scheduling in IEEE 802.16. An OFDMA slot can be characterized as a $\{$subchannel, symbol$\}$-tuple in the frequency and time domain. Vertical striping is used for both DL and UL subframes in the simulator, which means that OFDMA slots are allocated in frequency first and then in time, i.e. the first symbol is filled with data before the next symbol.

C. Propagation Model

The propagation model used in the simulator is the COST Hata path loss model, configured for suburban scenarios. Both the BS and CPEs are configured with 36 dBm transmit power. Antenna gains for both the BS and CPE are set to 0 dB. Dynamic transmit power adaptation is not implemented.

Further, the COST Hata model is combined with a Clarke-Gans implementation of Rayleigh fading, which has been extended to support 2048 subcarriers of the IEEE 802.22-2011. The Vehicular A ITU power delay spread model is used which is suited for the considered IEEE 802.22-2011 scenario with large cell in suburban areas and a tall BS antenna.

TABLE I

PER USER SESSION CONSIDERED TRAFFIC CHARACTERISTICS OF THE IEEE 802.22-2011 QOS CLASSES (IN CASE OF DETERMINISTIC DISTRIBUTION A SINGLE VALUE IS ALWAYS GENERATED)

	VBR		Video		VoIP		
	Packet size	Interarrival	Packet size	Interarrival	Packet size (ON)	Interarrival (ON)	ON/OFF period
Distribution	Deterministic	Determinstic	From trace	Deterministic	Deterministic	Deterministic	Exponential
Parameters	1500 B	0.33 ms	[10]	33 ms	66 B	20 ms	1.34 s (ON) 1.67 s (OFF)
Average rate	5 Mbps		71.5 kbps		11.7 kbps		
QoS Profile	BE		BE		UGS		

TABLE II

NS-2 IMPLEMENTATION OF IEEE 802.22-2011 COMPARED WITH IEEE 802.16 [14] AND IEEE 802.22-2011 [13], [1] STANDARDS (SEE ALSO [2, TABLE I], [3, TABLE 1], [4, TABLE 8.1], [5, TABLE IV])

Parameter	IEEE 802.16e	IEEE 802.22-2011	NS-2
Bandwidth	10 MHz	{6, 7, 8} MHz	6 MHz
FFT Size	1024	2048	2048
Frequency/Channels	2.5-2.69 GHz	54-698 MHz	54–698 MHz
Frame size	5 ms	10 ms	10 ms
Duplexing method	TDD	TDD	TDD
Tx/Rx Transit Gap (TTG)	105.7 μs	210, 245, 279.8μs	210μs
Rx/Tx Transit Gap (RTG)	60 μs	81.8, 221.7, 350.3μs	81.8μs
Modulation types	{16,64}-QAM, QPSK	{16,64}-QAM, QPSK	{16,64}-QAM, QPSK
Coding rates	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4
Error correction coding	CC, CTC, LDPC	CTC/BTC	No (emulated)
Max power	BS: 43, CPE: 23 dBm	BS/CPE: 36 dBm	BS/CPE: 36 dBm
Assumed noise figure	BS: 4 dB, CPE: 7 dB	BS/CPE: 4-6 dB	BS/CPE: 4 dB
QoS classes	UGS, rtPS, ErtPS, nrtPS, BE	UGS, rtPS, ErtPS, nrtPS, BE	UGS, BE
Cyclic prefix mode	1/4, 1/8, 1/16, 1/32	1/4	1/4
OFDM mapping	Rectangular	DL: vert. UL: horiz.	vert.
Error protection	HARQ	ARQ	ARQ
Subcarrier. spacing	10.94 kHz	3.348/3.906/4.464 kHz	3.348 kHz
Useful symbol length	91.4 μs	298.7/256/224 μs	298.7 μs
Guard time	11.4 μs	37.34/32/28 μs	37.34 μs
Symbol duration	102.9 μs	373.3/320/280 μs	373.3 μs
Sampling frequency	11.2 MHz	6.857/8/9.145 MHz	6.857 MHz
Sampling period	0.18 ms	0.299/0.256/0.224 ms	0.299 ms
Symbols per frame	48	26/30/34	26
Used subcarriers	840	1680	1680
Guard and null subcarriers	184	368	368
Pilot subcarriers	DL: 120, UL: 280	DL/UL: 240	DL/UL: 240
Data subcarriers	DL: 720, UL: 560	DL/UL: 1440	DL/UL: 1440
Subcarriers/subchannel	DL: 24, UL: 28	DL/UL: 24	DL/UL: 24
Subchannels	DL: 30, UL: 35	DL/UL: 60	DL/UL: 60
Pilot location	Distributed	Distributed	Distributed
Power control	Distributed	Distributed	No
Subcarrier allocation	FUSC, PUSC, Cont.	PUSC	PUSC
Sensing strategy	N/A	optional	two-stage sensing
Coarse sensing duration	N/A	optional	1 ms
Fine sensing duration	N/A	optional	30 ms
Fine sensing interval	N/A	optional	∞ (event based)
Cooperative sensing	N/A	optional	”OR” rule
WM detection threshold	N/A	optional	–107 dBm (averaged over 200 kHz)

Interference modeling in the simulator, as described in detail in [12], is done at the subcarrier level by capturing packets from all IEEE 802.22-2011 transmitters and the signals from WM activity.

D. Error Protection

For error protection the IEEE 802.22-2011 standard uses ARQ. For error correction coding the IEEE 802.22-2011 uses convolutional turbo codes (CTC) and block turbo code (BTC), although only ARQ is implemented in NS-2.

E. Wireless Microphone Implementation

A typical analog WM in the TV bands uses a narrow bandwidth of 200 kHz, which amount to 68 active subcarriers in the NS-2 OFDMA simulator. Since an analogue WM most of the time focus the transmit power on a narrow part of the 200 kHz bandwidth, we assume that the WM on average uses half the bandwidth with 34 subcarriers when implementing the WM in the NS-2. In this case, if the WM transmits with 200 mW over the 34 subcarriers, the transmit power per subcarrier for the WM in the NS-2 is set to $0.2\,\mathrm{W} / 34 = 0.0059\,\mathrm{W}$.

The WM implementation will transmit consecutively in both downlink and uplink direction to simulate a realistic WM with 100% duty cycle. The modulation and coding rate is fixed to QPSK 1/2.

F. Wireless Microphone Detection Process

The main functions involved in PU detection in the IEEE 802.22-2011 standard are the spectrum manager at the BS and the spectrum automaton at the CPE which controls the spectrum sensing function and the geo-location function. All functions are implemented in NS-2, except for geo-location (due to the assumption of TV broadcast absence in the considered channel) and transmit power control limits. Since the transmit power control limits are not implemented, the IEEE 802.22-2011 will switch to a new channel if a WM is detected on that channel. If no channels are available IEEE 802.22-2011 will cease transmission.

1) Spectrum Manager: The spectrum manager specifies the set of channel lists, i.e. the backup, candidate and protected channel lists. This is done by communicating with the spectrum sensing function. In the IEEE 802.22-2011 standard a channel will originally get status as backup channel when sensed as unused every six seconds over a period of 30 seconds. In the CPE, the spectrum automaton is a lightweight version of the spectrum manager in the BS. The channel selection procedure randomly selects one of the available channels. In the case that a WM signal is received on all channels, the channel with lowest received signal strength below detection threshold from the WM is selected.

2) Spectrum Sensing Implementation: The spectrum sensing function can first be classified into in-band sensing, that senses the operating channel, and out-of-band sensing, that senses activity on other channels that potentially can be used by the IEEE 802.22-2011 system. Considering sensing strategy, two-stage sensing is advocated by IEEE 802.22-2011. At the coarse sensing stage (first stage) a simple energy detection is used for frequent and short sensing periods t_c. If coarse sensing detects a WM signal it switches to the fine sensing stage (second stage) that uses a more detailed WM detection process for a longer period t_s. A simple energy detector will also be used for fine sensing in the simulator. If a WM signal is detected by fine sensing then the operating channel is switched to one of the backup channels. However, if coarse sensing does not detect any WMs, an optional time-based approach has been implemented where fine sensing periods can be started at specific times.

Probability of detection p_d and probability of false alarm p_f are set in the simulation separately for coarse ($p_{d,c}$ and $p_{f,c}$, respectively) and fine sensing ($p_{d,s}$ and $p_{f,s}$, respectively). In the simulation we were able to manipulate p_d and p_f in order to simulate the performance with different sensing constraints. The effect of p_d and p_f on the IEEE 802.22-2011 will be lower and higher respectively for coarse sensing which senses for shorter periods and is more unreliable than fine sensing. Further, cooperative sensing with the OR rule is used, which is mandatory in the USA as specified in the IEEE 802.22-2011 standard [1, Sec. 8.6.1.3]. Therefore, the total system p_f and p_d can analytically be calculated as $p_f = 1-(1-p_{f,i})^N$ and $p_d = 1-(1-p_{d,i})^N$, where N is the number of cooperative sensing nodes and $p_{f,i}$ and $p_{d,i}$ is the probability of false alarm and detection for each single node, respectively.

Coarse sensing is carried out during allocated time periods at the end of the uplink OFDMA subframe, typically for $t_c = 1\,\text{ms}$. Sensing occurs at every second OFDMA frame. Quiet periods for fine sensing are scheduled at the MAC layer. The fine sensing period is typically set to $t_s = 30\,\text{ms}$, spanning three OFDMA frames.

In total four different sensing strategies will be considered in the evaluation:

- *Two-stage spectrum sensing* [1]: coarse sensing every second frame with duration $t_c = 1\,\text{ms}$, $p_{d,c} = 0.9$ and $p_{f,c} = 0.1$, in which coarse sensing detection triggers a fine sensing stage with duration $t_s = 30\,\text{ms}$, $p_{d,s} = 0.99$ and $p_{f,s} = 0.01$;
- *Two-stage consecutive spectrum sensing* [15]: same as above, but 3 consecutive coarse detections are needed before a fine sensing stage is triggered;
- *Single-stage-30 spectrum sensing*: only fine sensing with duration $t_s = 30\,\text{ms}$, $p_{d,s} = 0.99$ and $p_{f,s} = 0.01$, which is time based triggered every 0.5 seconds;
- *Single-stage-100 spectrum sensing*: only fine sensing with duration $t_s = 100\,\text{ms}$, $p_{d,s} = 1$ and $p_{f,s} = 0$, which is time based triggered every 0.5 seconds.

Finally, in IEEE 802.22-2011, and our NS-2 implementation, out-of-band sensing is performed during quiet periods allocated for the fine sensing periods, and all relevant channels are sensed during one fine sensing period.

G. System Performance Metrics

Different performance metrics are used for the system level performance evaluation depending on the studied scenario. The metrics used to evaluate IEEE 802.22-2011 performance are:

- Throughput: measured at the transport layer for the actual application used (VBR, video or VoIP). This will not reflect the physical layer throughput which includes management frames for the MAC layer and the general network layer overhead.
- Delay: measured at the application layer as the time from the packet is transmitted until it is received. Delay will include queuing delay at all layers of the protocol stack.
- Packet Loss: measured at the network layer as the percentage of packets transmitted but not received.
- Packet Drops: a measure of packets dropped at the end of the BS queue due to congestion on the wireless link. Separate queues are implemented for the BE and UGS QoS profiles in the scheduler at the BS. Also, the BS holds a separate queue for each CPE. Queue length is 50 packets. First the BS transmits all packets enqueued in the UGS queues, next the remaining resources are allocated fairly to packets from the BE queues. All queues drop packets at the tail.
- SINR: is the Signal to Interference plus Noise Ratio measured per received packet at the CPE resulting from Gaussian noise and interference from the WMs.

Furthermore, to assess the impact on the WM performance we use the following metric:

- WM C/I: is the carrier to interference ratio measured at the WM, which is considered as the metric that best describes the performance of the analog WM. Noise is assumed to be Gaussian and therefore the only interference

TABLE III
PARAMETER VALUES FOR THE SIMULATION SCENARIOS (SEE ALSO [2, TABLE II])

Parameter	BS	CPE	WM
Nodes	1	4	4 pairs
Location	Fixed	Random	Random
Height (m)	30	5	1.5
Transmit Power (W)	4	4	0.2
Antenna Gain (dBi)	0	0	0
Modulation/FEC	16-QAM 1/2	16-QAM 1/2	QPSK 1/2
Channel bandwidth (MHz)	6	6	0.2
Channels used (MHz)	575–593	575–593	575–593

will be from the IEEE 802.22-2011 BS in the downlink and CPEs in the uplink.

All these metrics are measured locally at the actual device, i.e. at the transmitting BS for packet drops, at the receiving CPE for throughput, delay, packet loss and SINR, and at the WM for C/I. The performance metrics will mostly be presented as one average value for all CPEs and WMs.

IV. PERFORMANCE EVALUATION

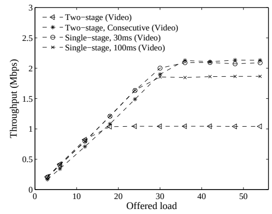
The specific values for the simulation scenarios are summarized in Table III. In the IEEE 802.22-2011 network, totally 4 CPEs are connected to 1 BS which applies to a sparsely populated area. In this area there are totally 4 channels of 6 MHz not used by the TV broadcasters and therefore available for the IEEE 802.22-2011 network. Furthermore, there are 4 WM pairs that each appear randomly on one of the 4 channels separately, hence the IEEE 802.22-2011 network has to switch channel when a WM appears on the operating channel. The distance between two WMs in a WM pairs is 150 m.

A. Evaluation of Simultaneous Multimedia Traffic with different QoS Profiles

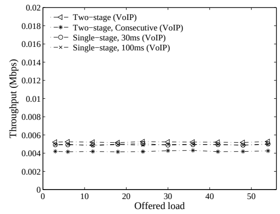
In this scenario four CPEs are present, where three CPEs receive video streams and one CPE establishes a VoIP connection (generating offered load of 0.0051 Mbps). The CPEs and WMs are located at a random position within 1 km from the BS, hence the CPEs will not experience outage due to a weak link. In the simulations, we let video traffic load increase by adding additional video sessions to each CPE, while VoIP traffic load remains constant. The WM activity is described by average inter-arrival time $1/\lambda_w = 10$ s and average occupancy time $1/\mu_w = 3$ s.

For the results given in Fig. 1, the offered load on the x-axis, as used in [8], denotes the offered load as the number of CPEs added with the number of video sessions per CPE. There are constantly 3 CPEs and the number of video sessions will increase in the range from 1 to 18 (generating a change in offered load from 0.215 to 3.86 Mbps). Simulations are run for all sensing strategies described in Section III-F2.

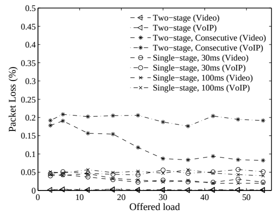
1) Throughput: Throughput for video traffic is given in Fig. 1(a) and for VoIP traffic in Fig. 1(b). For video throughput, we observe that the two-stage consecutive sensing achieves the highest throughput of the considered sensing strategies, which is explained by the aggressiveness of this sensing strategy requiring consecutive sensing before the channel is vacated. In other words, higher throughput is achieved at the cost of longer WM detection time. A second reason for higher throughput is the fact that since consecutive detections are needed before fine sensing is triggered, the effect of false alarms is reduced significantly. However, it is observed that the two-stage consecutive sensing achieves lower throughput than the other sensing strategies when the load does not congests the network, which is explained by the fact that packet loss is higher for two-stage consecutive sensing as observed in Fig. 1(c). This indicates that two-stage consecutive sensing might be preferable to achieve high throughput, but not if the packet loss rate is critical.



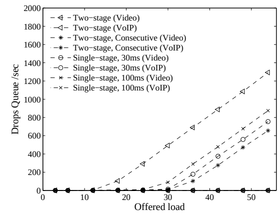
(a) Aggregate CPE video Throughput



(b) Aggregate CPE VoIP Throughput



(c) CPE Packet Loss



(d) Dropped packets in queue

Fig. 1. System performance of IEEE 802.22-2011 for simultaneous VoIP and video transmission: three CPEs receiving video traffic with increasing number of sessions and one CPE receiving VoIP with one session.

It is observed that two-stage sensing achieves the highest throughput for low offered load, but that throughput congests before the other sensing strategies when offered load increases. This is because two-stage sensing with the high number of coarse sensing stages with high probability of false alarm frequently triggers fine sensing immediately, which adds overhead and therefore reduces time available for data transmission. This indicates that two-stage sensing with coarse sensing stages every second OFDMA frame might not be preferred to achieve high throughput. However, it is found that two-stage sensing is superior for low detection time and protection of the WM when compared with the other sensing strategies.

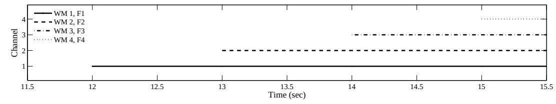
For VoIP throughput, we observe that two-stage consecutive sensing achieves lower throughput than the other sensing strategies. This is explained by the higher packet loss for VoIP traffic with two-stage consecutive sensing compared to the other sensing strategies, see Fig. 1(c), which for two-stage consecutive sensing actually on average is higher for VoIP than for video traffic. It is observed that the throughput is quite constant irrespective of the offered load, because the UGS QoS profile guarantees the bit rate and packet interval for the VoIP session. Two-stage sensing achieve slightly higher throughput than the single-stage sensing strategies due to the lower packet loss.

2) Packet Loss: It is observed that average packet loss for the IEEE 802.22-2011 CPEs given in Fig.1(c) is highest for two-stage consecutive sensing, both for VoIP with average 0.20% and video with average 0.12%. This is because two-stage consecutive sensing is more aggressive requiring consecutive detections before vacating the channel, hence packets will opportunistically be transmitted in cases where an active WM might be nearby causing interference. The other three sensing strategies have much lower packet loss since action is taken immediately when a WM is first detected, and since probability of detection is higher for the single-stage sensing strategies. For two-stage sensing, packet loss is on average 0.001% for video and 0.002% for VoIP. Difference in packet loss is on average almost equal for the three other sensing strategies. From the observed packet loss levels it can be concluded that the interference in the considered scenario is neglectable.

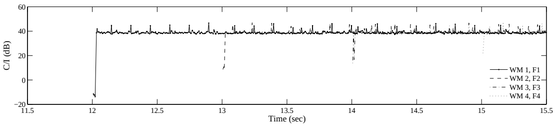
If one looks in the offered load region, it is observed that VoIP traffic in general has higher loss than video traffic. However, packet loss is almost equal for VoIP and video for low offered load of video traffic. It is especially observed that packet loss for video with two-stage consecutive sensing tends to go down as the offered load increases, which is because when the offered load increases the momentarily impacts from the WMs on the overall percentage of packet loss reduces. This is also observed for the other three sensing strategies, but to a much lower extent.

3) Packet Drops: The packet drop rate at the end of the BS queue is presented in Fig. 1(d). The two-stage consecutive sensing is more aggressive than the others, hence more packets are transmitted by the IEEE 802.22-2011 BS and less packets are dropped at end of the queue. It is seen that queue drops for video increase sharply at a certain offered load of video traffic (e.g 18 for two-stage sensing and 36 for two-stage consecutive sensing), which is because all bandwidth is utilized at this offered load. Queue drops are not observed for VoIP traffic since the BS scheduler maintains different queues for VoIP and video where VoIP with UGS QoS profile has a guaranteed bit rate and priority over video with BE QoS profile.

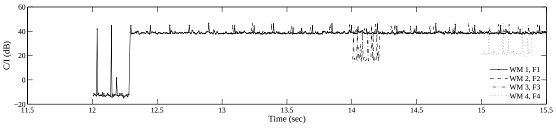
4) Delay: Average delay for VoIP was measured to be constant irrespective of the offered load, with an average delay of 39.3 ms for two-stage, 11.1 ms for two-stage consecutive, 13 ms for single-stage-30 and 25.5 ms for single-stage-100 sensing. This indicates that the overhead caused by the sensing strategy has a great impact on delay. For a low offered load, video delay was similar to VoIP, but increased slightly as offered load increased and increased dramatically when the network was congested, because packets stayed longer in the BS queue (as it was found in [5]). This indicates that VoIP traffic using the UGS profile is prioritized in the IEEE 802.22-2011 standard in favor of the BE traffic. However, it is noted that this is dependent on the WM activity level and the availability of at least one channel when there are VoIP packets to be transmitted.



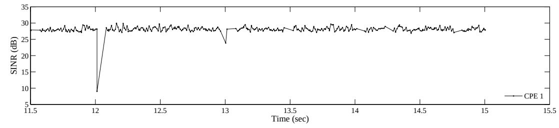
(a) WM appearance scheme on channels



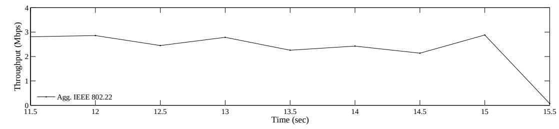
(b) C/I experienced by WMs for two-stage sensing



(c) C/I experienced by WMs for single-stage-30 sensing



(d) SINR experienced by CPE 1 for two-stage sensing



(e) Aggregate throughput for all CPEs for two-stage sensing

Fig. 2. Instantaneous impact on C/I experienced by the WMs.

B. Instantaneous Impact of IEEE 802.22-2011 Network on WMs

From the previous experiments we noticed that the interference to WMs was only caused for a short period before IEEE 802.22-2011 sensing stage detected the WM. To illustrate this we performed an experiment to measure instantaneous interference to the WM by simulations in the time interval from 10 s to 20 s. Initially, the IEEE 802.22-2011 system operates on F1 with 4 CPEs located at (x,y) m coordinates: CPE 1 at (500,0) m, CPE 2 at (0,500) m, CPE 3 at (–500,0) m and CPE 4 at (0,–500) m. The WM appearance pattern is illustrated in Fig. 2(a), where WM 1 appears on F1 at location (100,0) m: at time 12 s, WM 2 at F2 at location (0,400) m: at time 13 s, WM 3 at F3 at location (–600,0) m: at time 14 s and WM 4 at F4 at location (0,–1000) m: at time 15 s. When a WM first appears it will stay on the channel until the end of the simulation as illustrated in Fig. 2(a), hence the IEEE 802.22-2011 system will switch consecutively to the higher channel as the WMs appear. For illustration purposes, $p_{d,c} = 0.99$ and $p_{f,c} = 0.01$.

This experiment was performed both for two-stage sensing and for single-stage sensing as given in Fig. 2(b) and Fig. 2(c), respectively, where experienced C/I for the 4 WMs is presented for the entire simulation time. A first observation is that the instantaneous interference for single-stage sensing is higher than that of two-stage sensing, which is because the intervals between sensing is longer for single-stage sensing and hence the time before the WM is detected is longer. A second observation is that the lowest instantaneous C/I levels observed for each WM is higher for WM $x-1$ than WM x. The reason for this is that since the distance between the BS and WM $x-1$ is lower than between BS and WM x, the DL traffic transmitted by the BS will interfere more with WM $x-1$ than WM x. A third observation is that there is no interference when WM 2 appears when single-stage sensing is used, which is because the IEEE 802.22-2011 system is in a single-stage sensing period when WM 2 appears.

We also present the SINR experienced by CPE 1 for the two-stage sensing strategy in Fig. 2(d). It can be seen that WM 1 interfere more than the other WMs since WM 1 is closest to CPE 1. At times when a WM appears and SINR reduces, it can be seen that it takes longer time before the next SINR measurement is obtained, since fine sensing is triggered and the IEEE 802.22-2011 system switches channel. In general, interference to CPE 1 is not very high since the distance to the BS is short and since the narrow-band WM only interferes with few packets and then often with a subset of the subcarriers used.

Aggregate throughput for all CPEs is presented in 2(e), where it is seen that throughput reduces especially when the WM appears. Also, it is observed that throughput reduces more when WMs appear closer to the CPEs but at farther distance from the BS, since these CPEs have lower link budget. After 15 s the IEEE 802.22-2011 system does not find any available channels.

V. Conclusions

We have studied the network level performance of IEEE 802.22-2011 with sensing functionality in terms of throughput, delay, packet loss and interference by implementing an extensive network level simulator in NS-2. The analysis showed that the performance for different sensing strategies should be considered dependent on the required QoS. It was found that average delay increased with respect to the overhead caused by the sensing strategy used in the IEEE 802.22-2011 network and that VoIP traffic can be prioritized to achieve lowest possible delay for the specific sensing strategy irrespective of the best effort traffic load. The impact on the WMs was found to be low in general and we demonstrated that interference was caused only for short intervals when the WM appeared. A tradeoff for the selection of sensing strategy was found between achieving high capacity in the IEEE 802.22-2011 network and protecting the wireless microphones at a highest possible level.

Acknowledgments

Part of this research was supported by the Dutch Technology Foundation STW under contract 12491.

References

[1] *IEEE Standard for Information Technology–Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)–Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands*, IEEE IEEE Std 802.22-2011, 2011.

[2] P. Grønsund, P. Pawelczak, J. Park, and D. Cabric, "Sensing of wireless microphones in IEEE 802.22: A system level performance evaluation," in *Proc. IEEE ICC*, Budapest, Hungary, Jun. 9–13, 2013.

[3] P. Grønsund, P. E. Engelstad, P. Pawelczak, O. Grøndalen, P. H. Lehne, and D. Cabric, "Spectrum sensing aided long-term spectrum management in cognitive radio networks," submitted to IEEE Local Computer Networks Conference 2013.

[4] P. Pawelczak, J. Park, P. Grønsund, and D. Cabric, "System level analysis of OFDMA-based networks in TV white spaces: IEEE 802.22 case study," in *TV White Space Spectrum Technologies: Regulations, Standards, and Applications*, R. A. Saeed and S. J. Shellhammer, Eds. CRC Press, 2011.

[5] J. Park, P. Pawelczak, P. Grønsund, and D. Cabric, "Analysis framework for opportunistic spectrum OFDMA and its application to IEEE 802.22 standard," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2271–2293, Jun. 2012.

[6] *IEEE Draft Standard for Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements Part 22.1: Standard to Enhance Harmful Interference Protection for Low Power Licensed Devices Operating in TV Broadcast Bands*, IEEE Std. P802.22.1 Draft 8, Jul. 2010.

[7] P. A. Lambert, "White spaces: Requirements discussion," IETF PAWS Digest, vol. 6, no. 18, Jul. 2011.

[8] C. Cicconetti, A. Erta, L. Lenzini, and E. Mingozzi, "Performance evaluation of the IEEE 802.16 MAC for QoS support," *IEEE Trans. Mobile Comput.*, vol. 6, no. 1, pp. 26–38, Jan. 2007.

[9] P. T. Brandy, "Model for generating on-off speech patterns in two-way conversation," *J. Acoust. Soc. Am.*, vol. 46, no. 1A, pp. 109–109, 1969.

[10] F. H. P. Fitzek and M. Reisslein, "MPEG-4 and H.263 video traces for network performance evaluation," *IEEE Netw.*, vol. 15, no. 6, pp. 40–54, Nov./Dec. 2001.

[11] M. Wellens, J. Riihijärvi, and P. Mähönen, "Empirical time and frequency domain models of spectrum use," *Elsevier Physical Communication Journal*, vol. 2, no. 1–2, pp. 10–32, Mar.–Jun. 2009.

[12] N. Golmie, R. Rouil, D. Doria, X. Guo, R. Iyengar, S. Kalyanaraman, S. Krishnaiyer, S. Mishra, B. Sikdar, R. Jain, R. Patneyand, C. So-In, and S. Parekh. (2009) WiMAX forum system level simulator NS-2 MAC+PHY add-on for WiMAX (IEEE 802.16). [Online]. Available: http://code.google.com/p/ns2-wimax-awg/

[13] C. R. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. J. Shellhammer, and W. Caldwell, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 130–138, Jan. 2009.

[14] *Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1*, IEEE Std. 802.16e, Apr. 2006.

[15] W. S. Jeon, D. G. Jeong, J. A. Han, G. Ko, and M. S. Song, "An efficient quiet period management scheme for cognitive radio systems," *IEEE Trans. Wireless Commun.*, vol. 7, no. 2, pp. 505–509, Feb. 2008.

Paper G
Sensing of Wireless Microphones in IEEE 802.22: A System Level Performance Evaluation

Pål Grønsund, Przemysław Pawełczak, Jihoon Park and Danijela Čabrić

IEEE International Conference on Communications (ICC), Budapest, Hungary, Jun. 9-13, 2013.

Sensing of Wireless Microphones in IEEE 802.22: A System Level Performance Evaluation

Pål Grønsund*†, Przemysław Pawełczak‡, Jihoon Park§, and Danijela Cabric¶
*Telenor, Snarøyveien 30, 1331 Fornebu, Norway
†University of Oslo, Gaustadallen 23, 0373 Oslo, Norway
‡Delft University of Technology, Mekelweg 4, 2628 CD, Delft, The Netherlands
§Samsung Electronics Co., Maetan 3-dong, Yeongtong-gu, Suwon-si, Gyeonggi-do, South Korea, 443-742
¶University of California, Los Angeles, 56-125B Engineering IV Building, Los Angeles, CA 90095-1594, USA
Email:*pal.gronsund@telenor.com, ‡p.pawelczak@tudelft.nl,§jpark0@samsung.com,¶danijela@ee.ucla.edu

***Abstract*—We present results on the system level performance of the IEEE 802.22 standard with sensing functionality, using a highly detailed implementation of the IEEE 802.22 protocol stack in the NS-2 simulator. Our attention is focused on the effect of spatio-temporal wireless microphone (WM) activity on the performance of the IEEE 802.22 network with spectrum sensing considered. In general we find that the frequency of WM appearance and activity duration should be quite high in all channels not used by TV broadcasters to reduce IEEE 802.22 throughput, for example about 50% WM occupancy in each of total of four channels. Impact on WM performance is found to be low in general using the two-stage spectrum sensing strategy with frequent sensing stages.**

I. Introduction

A number of standardization and regulatory bodies work towards a better exploitation of the TV white spaces [1]. The IEEE 802.22 [2] standard published in 2011 is the first, most sophisticated and one of the most discussed standards for operation in TV white spaces [3]. In short, the system specified in the IEEE 802.22 standard utilizes TV white spaces to provide a fixed broadband service in the rural areas.

The IEEE 802.22 devices use geo-location and communicate with a database to obtain information about available frequencies and allowed transmit power levels at their locations. In addition the IEEE 802.22 system can use sensing techniques to detect sudden appearance of primary users of the TV bands such as TV transmitters and Wireless Microphones (WMs). The TV broadcasters update the database about their frequency usage and transmit power levels at all locations. Other low power devices operating in these bands such as WMs might update the database, but might also appear suddenly at random locations without notification. Detection and protection of these WMs are considered as one of the greatest challenges for the IEEE 802.22 system. By using sensing technologies, the IEEE 802.22 system should be able to detect WMs and then cease transmission and switch to a vacant TV channel.

Understanding the complete system level performance of IEEE 802.22 is complex and difficult to achieve with analytical models. Therefore, we have developed the most complete implementation of the IEEE 802.22 stack in the NS-2 simulator. This simulation software was used in our other related works to: (a) evaluate delay at the application layer of IEEE 802.22 [4]; (b) evaluate different QoS profiles (e.g. video and voice over IP) in IEEE 802.22 [5], (c) evaluate IEEE 802.22 network as a function of Customer Premises Equipment (CPE) to Base Station (BS) distance (for different power and modulation levels of IEEE 802.22 CPE and varying WM power) [6]; and (d) four channel selection techniques IEEE 802.22 based on WM signal characteristics [7].

In this paper we present further detailed system level performance evaluation of IEEE 802.22. The new contribution is the detailed study of the impact of temporal activity of WM on the IEEE 802.22 network.

Parts of this work has been supported by the Dutch Technology Foundation STW under contract 12491.

II. System Model

For the ease of reading we re-introduce the system model of our NS-2 IEEE 802.22 implementation, which is also found and introduced in [4], [5], [6], [7].

A. IEEE 802.22 Network Model

We consider an IEEE 802.22 system limited to one BS and a set of CPEs fixed at certain locations in accordance with the IEEE 802.22 standard. An example network setup is illustrated in Fig. 1 with four CPEs and four WM Tx-Rx pairs. The small oval illustrates the coverage area for WM 1a and the big oval the coverage area for the IEEE 802.22 BS. The simulator supports all channels in the UHF band, but a subset of channels are selected for operation in the studied simulation scenarios, exactly four channels using the frequencies denoted F1–F4. A personal computer (PC) connected via Ethernet to the BS will establish links to the CPEs and run traffic models.

In this study we assume that TV transmissions are known from the database and focus only on WMs as the primary users. WM activity will be detected only by sensing techniques with no support from beacon protocol like IEEE 802.22.1 [8]. Finally, the IEEE 802.22 self coexistence protocol is not used since a single cell is considered.

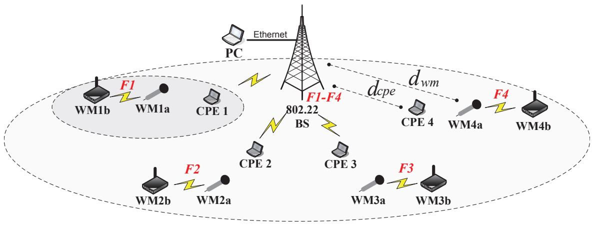


Fig. 1. Illustration of the IEEE 802.22 network model used in the evaluation; [7, Fig. 1], [6, Fig. 1.1].

B. Traffic Model

1) IEEE 802.22 Traffic Model: The traffic model variable bit rate (VBR) is used to measure the maximum IEEE 802.22 system throughput. VBR will run over UDP where maximum rates will be simulated by constantly transmitting UDP packets to each CPE of size 1500 Bytes every 0.33 ms, which amounts to a bit rate higher than the channel capacity. VBR will use the best effort (BE) QoS traffic profile in IEEE 802.22 which provides fairness between the CPEs using the BE profile.

2) Wireless Microphone Traffic Model: When the WM becomes active, its traffic pattern is characterized by a 100% duty cycle (irrespective whether someone is speaking to the microphone or not) until the WM disappears. It should be noted that the NS-2 simulator is packet transmission-based, hence we assume that WM virtually transmits data packets consecutively during the whole IEEE 802.22 OFDMA frame in order to simulate the 100% duty cycle traffic pattern.

We are not aware of any statistics on WM traffic distribution, hence we assume that all WMs generate new connections according to the negative exponential distribution for the average inter-arrival time $1/\lambda_w$ and average occupancy time $1/\mu_w$ which is common in wireless communications [9].

III. Simulation Model

Again, for the ease of exposition we re-introduce the system model of our NS-2 IEEE 802.22 implementation, which is also found in [4], [5], [6], [7]. In this study we adapt an extensive implementation of IEEE 802.16e in NS-2 [10] developed for the WiMAX Forum [11] to implement the IEEE 802.22 standard. The features that are different from IEEE 802.16 are implemented and conform to the best extent to the functional requirements as specified in the IEEE 802.22 standard. Note that the main parameters of our IEEE 802.22 NS-2 simulator, in relation to IEEE 802.22 standard, are presented in [5, Table II], [4, Table IV], [6, Table 8.1], and [7, Table I].

A. OFDMA and Channelization Structure

Both the IEEE 802.22 downlink and uplink subframes have totally 60 subchannels, where each subchannel consists of 28 subcarriers out of which 24 data and 4 pilot subcarriers. The IEEE 802.22 network can operate on any vacant TV channel not used by the primary user. Channel bonding of scattered available channels is not considered in this study, therefore only one available UHF channel will be used by the IEEE 802.22 system at any time. A WM occupies only one channel.

In our IEEE 802.22 NS-2 implementation only the 6 MHz profile is used. For the subcarrier allocation strategy, partially used subcarrier (PUSC) allocation [12] is used. Guard bands are considered at both ends of the channel bandwidths with a total of 368 guard and null subcarriers.

The transmit/receive transition gap (TTG) is set to 210 μs, which supports a 30 km distance between BS and CPE. A dynamic TTG is needed for greater distances, however this is not implemented since the simulation scenarios considered involve only small distances. The receive/transmit transition gap (RTG) is set to 81.8 μs. There are totally 26 symbols, each of 373.33 μs duration. The DL:UL ratio is set to 2:1.

B. OFDMA Traffic Scheduling

The MAC layer of IEEE 802.22 uses linear scheduling to allocate OFDMA slots to traffic from the upper layers in both the downlink and uplink subframes, as opposed to a rectangular scheduling in IEEE 802.16. An OFDMA slot can be characterized as a {subchannel, symbol}-tuple in the frequency and time domain. Vertical striping is used for both DL and UL subframes in the simulator, which means that OFDMA slots are allocated in frequency first and then in time, i.e. the first symbol is filled with data before the next symbol.

C. Propagation Model

The propagation model used in the simulator is the COST Hata [13] path loss model, configured for suburban scenarios. Further, the COST Hata model is combined with a Clarke-Gans [14] implementation of Rayleigh fading, which has been extended to support 2048 subcarriers for IEEE 802.22. The Vehicular A ITU power delay spread model [15] is used which is suited for the considered IEEE 802.22 scenario with large cell in suburban areas and a tall BS antenna. Both the BS and CPEs are configured with 36 dBm transmit power. Antenna gains for both the BS and CPE are set to 0 dB. Dynamic transmit power adaptation is not implemented.

Interference modeling is done at the subcarrier level by capturing packets from all IEEE 802.22 nodes and WMs. When the received signal to interference plus noise ratio (SINR) on each subcarrier is calculated for each packet, a decision is made to further process or drop the packet. This is done by first finding the exponential effective SIR mapping (EESM) [16] to get the effective SINR and then extracting the block error rate (BLER) from the SINR, modulation and coding rate and block size. Based on the BLER value a decision is made whether to drop the packet or not[1].

D. Error Protection

Channel errors are considered in the simulations. For error protection the IEEE 802.22 standard uses ARQ. For error correction coding the IEEE 802.22 uses convolutional turbo codes (CTC) and block turbo code (BTC), although only ARQ

[1]Please refer to [10] for a detailed description of of the OFDMA physical layer implementation and interference modeling. Note that the propagation model, operating frequency range and system profiles are reimplemented to fit the UHF bands, IEEE 802.22 and suburban scenarios.

is implemented in NS-2. However, if BLER found as described in Section III-C is above a threshold set to 4% (recommended by the WiMAX Forum IEEE 802.16e implementation [11]) the simulator emulates that the erroneous bits are corrected.

E. Wireless Microphone Implementation

A typical analog WM in the TV bands uses a narrow bandwidth of 200 kHz, which amount to 68 active subcarriers in the NS-2 OFDMA simulator. Since an analogue WM most of the time focuses transmit power on a narrow part of the 200 kHz bandwidth, we assume that the WM on average uses half the bandwidth with 34 subcarriers when implementing the WM in the NS-2 simulator. In this case, if the WM transmits with 200 mW, the transmit power per subcarrier for the WM is set to 0.2 W/34=0.0059 W in the NS-2 simulator. The WM implementation will transmit consecutively in both directions to simulate a realistic WM with 100% duty cycle. The modulation and coding rate is QPSK 1/2.

F. Wireless Microphone Detection Process

The main functions involved in primary user detection in the IEEE 802.22 standard are the spectrum manager at the BS and the spectrum automaton at the CPE which controls the spectrum sensing and the geo-location function. All functions are implemented in NS-2, except for geo-location (due to the assumption of TV broadcast absence in the considered channel) and dynamic transmit power control. Since the latter is not implemented, the IEEE 802.22 will switch to a new channel if a WM is detected on that channel. If no channels are available IEEE 802.22 will cease transmission.

G. Spectrum Manager

The spectrum manager is implemented in the BS and is responsible for deciding which channel to use. It specifies the set of channel lists, i.e. the backup, candidate and protected channel lists. In the IEEE 802.22 standard a channel will get status as backup channel when sensed as unused every six seconds over a period of 30 seconds. An algorithm can be applied to optimize which of the backup channels will be selected as the operating one, which in our NS-2 simulator will be the first available channel in the list.

In the CPE, the spectrum automaton is a lightweight version of the spectrum manager in the BS. The spectrum automaton is controlled by the BS and is mostly responsible for reporting information to the spectrum manager. In rare cases, the spectrum automaton itself is responsible for sensing at initial CPE power on, when it looses contact with the BS and during an idle time when there are no tasks pending.

1) Spectrum Sensing Implementation: The spectrum sensing function can first be classified into in-band sensing, that senses the operating channel, and out-of-band sensing, that senses activity on channels that potentially can be used by the IEEE 802.22 system. For in-band sensing, the two-stage spectrum sensing approach, as specified by the standard, is implemented in the simulator. At the coarse sensing stage (first stage) a simple energy detection is used for frequent and short sensing periods, $t_c = 1\,\text{ms}$ in the simulator. If coarse sensing detects a WM signal, it switches to the fine sensing stage (second stage) that uses a more detailed WM detection process for a longer period, $t_s = 30\,\text{ms}$ in the simulator (spanning three OFDMA frames). A simple energy detector is also used for fine sensing in the simulator. Coarse sensing is carried out during allocated time periods at the end of the uplink OFDMA subframe, and occurs at every second OFDMA frame. If a WM signal is detected by fine sensing then the operating channel is switched to one of the backup channels.

Probability of detection p_d and probability of false alarm p_f are set in the simulation separately for coarse and fine sensing. In the simulation we were able to manipulate p_d and p_f in order to simulate performance with different sensing constraints. The effect of p_d and p_f on the IEEE 802.22 will mostly be considered for coarse sensing which is more unreliable than fine sensing. Fine sensing that uses more advanced sensing techniques is considered to be more accurate and p_d and p_f are therefore set to one and zero, respectively. Further, cooperative sensing with the OR rule is implemented for all sensing stages, which is mandatory in the US as specified in the IEEE 802.22 standard [2, Sec. 8.6.1.3].

Finally, in IEEE 802.22, and our NS-2 implementation, out-of-band sensing is performed during quiet periods allocated for the fine sensing periods, and all relevant channels are sensed during one fine sensing period.

IV. System Performance Metrics

Just like in [4], [5], [6], [7] different metrics are used to evaluate the performance of the IEEE 802.22 standard depending on the studied scenario. The metrics used to evaluate IEEE 802.22 performance are:

1) Throughput: measured at the transport layer for the actual application used. This will not reflect the physical layer throughput which includes management frames for the MAC layer and the general network layer overhead.
2) Packet Loss: measured at the network layer as the percentage of packets transmitted but not received.
3) SINR: Signal to Interference plus Noise Ratio at the CPE resulting from Gaussian noise and interference from WMs.

Furthermore, to assess the impact on the WM performance we use the following metrics:

1) WM C/I: is the carrier to interference ratio measured at the WM, which is considered as the metric that best describes the performance of the analog WM. Noise is assumed to be Gaussian and therefore the only interference will be from the IEEE 802.22 BS in the downlink and CPEs in the uplink.

All metrics are measured locally at the actual device, i.e. at the receiving CPE for throughput, packet loss and SINR, and at the WM for C/I. The metrics will mostly be presented as one average value for all CPEs and WMs.

TABLE I
PARAMETER VALUES FOR THE SIMULATION SCENARIOS; COMPARE WITH [5, TABLE III]

Parameter	BS	CPE	WM
Nodes	1	4	4 pairs
Location	Fixed	Random	Random
Height (m)	30	5	1.5
Transmit Power (W)	4	4	0.2
Antenna Gain (dBi)	0	0	0
Modulation/FEC	16-QAM 1/2	16-QAM 1/2	QPSK 1/2
Prob. of false alarm (p_f)	0.01	0.01	—
Prob. of detection (p_d)	0.99	0.99	—
Channel bandwidth (MHz)	6	6	0.2
Channels used (MHz)	575–593	575–593	575–593

V. PERFORMANCE EVALUATION: IMPACT OF THE TEMPORAL ACTIVITY OF WMS ON THE IEEE 802.22 NETWORK

The specific values for the simulation scenarios are summarized in Table I. In the IEEE 802.22 network as illustrated in Fig. 1, totally 4 CPEs are connected to 1 BS which applies to a sparsely populated area. In this area there are totally 4 channels of 6 MHz not used by the TV broadcasters and therefore available for the IEEE 802.22 network. Furthermore, there are 4 WM pairs that each appear randomly on one of the 4 channels separately, hence the IEEE 802.22 network has to switch channel when a WM appears on the operating channel. The distance between two WMs in a WM pairs is set to 150 m. Note that some parameters will be changed for the simulation scenarios, but this will be stated clearly.

Each simulation is run 15 times, each with a duration of 500 s, and the results are averaged. A warm up time of 20 s is used to ensure that a stable point of network operation is reached. Considering that in NS-2 all nodes will receive packets from all other nodes within detection range, irrespective of actual frequency used, and that the nodes processes the packet fully or partially, each single simulation takes about 45 minutes on a modern computing cluster[2].

The 4 WM pairs appear on separate channels randomly within a radius of 1 km. Also, each CPE is located randomly within 1 km from the BS. The short radius used in this scenario is to assure that WMs are detected according to the p_d and p_f. For the spectrum sensing, as a special case, only the BS does two-stage spectrum sensing with $t_c = 1\,\text{ms}$ and $t_s = 30\,\text{ms}$.

In reality, WMs appear very infrequently and operate for short durations, i.e. in the order of hours. To be able to simulate the WM activity we scale the realistic $1/\lambda_w$ and $1/\mu_w$ to values resulting in short simulation time. The scaling will not impact the physical layer performance metrics, but will impact on the higher layer metrics throughput and packet loss for very low values of $1/\lambda_w$ and $1/\mu_w$ when $1/\lambda_w < 1/\mu_w$. This will result in lower bound values for the metrics of interest. In most simulations, however, this will not be an issue.

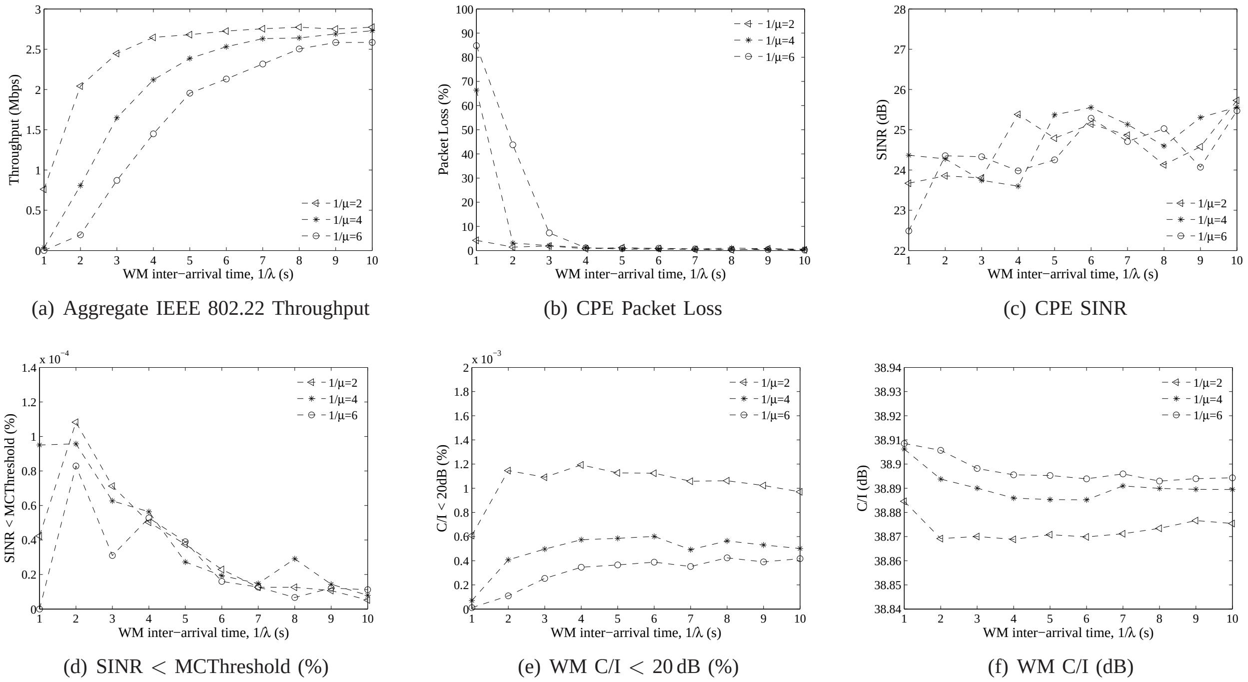
2) Throughput: Average aggregate throughput for the CPEs versus increasing WM inter-arrival times in the range $1/\lambda_w = 1, \ldots, 10\,\text{s}$ for the occupancy times $1/\mu_w = \{2, 4, 6\}$ s is given in Fig. 2(a). A first observation is that maximum throughput achieved in the downlink is 2.76 Mbps, which is in accordance with the standard when considering overhead from higher layer protocols and sensing. A saturation in throughput is observed when inter-arrival time $(1/\lambda_w)$ increases because the probability of finding an opportunity to transmit in all channels increases. It is also observed that $1/\mu_w = 2\,\text{s}$ saturates before $1/\mu_w = 4\,\text{s}$ and $1/\mu_w = 6\,\text{s}$ which is because the lower the occupancy time $(1/\mu_w)$, the positive value from $1/\lambda_w - 1/\mu_w$ becomes higher, hence the probability of finding an opportunity to transmit increases. It can also be observed that the lower the occupancy time $(1/\mu_w)$, the higher the throughput, which especially is visible for the lower inter-arrival times where $1/\mu_w < 1/\lambda_w$. This is also the reason for the observed distance between the curves where throughput increases when the WM occupancy times $(1/\mu_w)$ increases. As an overall observation, the frequency of WM appearance and activity duration should be quite high in all channels not used by the TV broadcaster to reduce IEEE 802.22 throughput.

3) Packet Loss: It can be seen that average packet loss for the CPEs given in Fig. 2(b) is higher for lower inter-arrival times $(1/\lambda_w)$ and especially for higher occupancy times $(1/\mu_w)$. When $1/\lambda_w \ll 1/\mu_w$ the probability that the IEEE 802.22 system will find an opportunity to transmit is extremely low. Then, when the IEEE 802.22 system first transmits the probability that a WM appears on that channel is extremely high. Consequently, the percentage of packet loss increases considerably due to interference from the WM.

4) SINR: It can be seen that average SINR for the CPEs presented in Fig. 2(c) increases as WM inter-arrival time increases. Lower SINR is seen for lower inter-arrival times because the actual time the IEEE 802.22 system is able to access the channel decreases. Hence, the number of packets that experience interference from the WM in proportion to the total number of packets received increases. This can also be illustrated by the average percentage of packets that obtain SINR below the modulation and coding threshold (MC-Threshold) for the IEEE 802.22 CPEs presented in Fig. 2(d), indicating harmful interference to the IEEE 802.22 CPE, which increases for lower WM inter-arrival times. We note that the number of simulations should be higher to obtain more accurate SINR result due to the random CPE location within the cell. However, a notable increase in SINR is seen in Fig. 2(c) for $1/\mu_w = 2\,\text{s}$ at $1/\lambda_w = 4\,\text{s}$, for $1/\mu_w = 4\,\text{s}$ at $1/\lambda_w = 5\,\text{s}$ and for $1/\mu_w = 6\,\text{s}$ at $1/\lambda_w = 6\,\text{s}$.

5) Impact on WMs: The percentage of time the WM experience C/I values below the required C/I level of 20 dB [17] given in Fig. 2(e) show that the higher the inter-arrival time $(1/\lambda_w)$, the more interference is caused to the WMs. This is because the probability that the IEEE 802.22 system transmits when a WM appears is higher the more $1/\lambda_w > 1/\mu_w$. However, we find that the interference is only caused at the instantaneous time when the WM appears, and in general it can be observed that the percentage of time the WM drops below the required C/I level is very low. The average WM C/I

[2]IBM cluster with dual quad core compute nodes Xeon L5420 / 2.5 GHz processors, each with 8 cores, 8 GB of memory and operating system linux Ubuntu Hardy Heron.



(a) Aggregate IEEE 802.22 Throughput (b) CPE Packet Loss (c) CPE SINR

(d) SINR $<$ MCThreshold (%) (e) WM C/I $<$ 20 dB (%) (f) WM C/I (dB)

Fig. 2. IEEE 802.22 performance for various WM inter-arrival times, $1/\lambda_w = \{1, \ldots, 10\}$ s, and average occupancy times $1/\mu_w = \{2, 4, 6\}$ s.

presented in Fig. 2(f) also confirms this.

VI. Conclusions

In this paper we have studied the network level performance of IEEE 802.22 with sensing functionality by means of an extensive network level simulations implemented in NS-2. We studied the throughput for different activity levels of wireless microphones (WMs) in channels not occupied by TV broadcasters, and found that the WM activity level should be quite high in all channels to reduce IEEE 802.22 throughput. For example, about 50% WM occupancy in each of total of four channels to reduce throughput remarkably. Impact on WM performance was found to be low in general using the two-stage spectrum sensing strategy with frequent sensing stages.

References

[1] Y.-C. Liang, A. T. Hoang, and H.-H. Chen, "Cognitive radio on TV bands: A new approach to prove wireless connectivity for rural areas," *IEEE Wireless Commun. Mag.*, vol. 15, no. 3, pp. 16–22, Jun. 2008.

[2] *IEEE Standard for Information Technology–Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)–Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands*, IEEE IEEE Std 802.22-2011, Jul. 2011.

[3] C. R. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. J. Shellhammer, and W. Caldwell, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 130–138, Jan. 2009.

[4] J. Park, P. Pawełczak, P. Grønsund, and D. Čabrić, "Analysis framework for opportunistic spectrum OFDMA and its application to IEEE 802.22 standard," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2271–2293, Jun. 2012.

[5] P. Grønsund, P. Pawełczak, J. Park, and D. Čabrić, "System level performance of IEEE 802.22 with sensing-based detection of wireless microphones," 2012, submitted to IEEE Commun. Mag.

[6] P. Pawełczak, J. Park, P. Grønsund, and D. Čabrić, "System level analysis of OFDMA-based networks in TV white spaces: IEEE 802.22 case study," in *TV White Space Spectrum Technologies: Regulations, Standards, and Applications*, R. A. Saeed and S. J. Shellhammer, Eds. CRC Press, 2011.

[7] P. Grønsund, P. E. Engelstad, P. Pawełczak, O. Grøndalen, P. H. Lehne, and D. Cabric, "Spectrum selection in cognitive radio networks with spectrum sensing aided long-term spectrum management," submitted to IFIP Networking 2013.

[8] *IEEE Draft Standard for Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements Part 22.1: Standard to Enhance Harmful Interference Protection for Low Power Licensed Devices Operating in TV Broadcast Bands*, IEEE Std. P802.22.1 Draft 8, Jul. 2010.

[9] M. Wellens, J. Riihijärvi, and P. Mähönen, "Empirical time and frequency domain models of spectrum use," *Elsevier Physical Communication Journal*, vol. 2, no. 1–2, pp. 10–32, Mar.–Jun. 2009.

[10] N. Golmie, R. Rouil, D. Doria, X. Guo, R. Iyengar, S. Kalyanaraman, S. Krishnaiyer, S. Mishra, B. Sikdar, R. Jain, R. Patneyand, C. So-In, and S. Parekh. (2009) WiMAX forum system level simulator NS-2 MAC+PHY add-on for WiMAX (IEEE 802.16). [Online]. Available: http://code.google.com/p/ns2-wimax-awg/

[11] WiMAX forum website. [Online]. Available: http://www.wimaxforum.org/

[12] (2006, August) Mobile WiMAX–part 1: A technical overview and performance evaluation. [Online]. Available: http://www.wimaxforum.org/resources/documents/marketing/whitepapers

[13] "COST 231. digital mobile radio towards future generation systems. final report," E. Demosso, Ed. Brussels, Belgium, EU: European Commission, 1999. [Online]. Available: http://www.lx.it.pt/cost231

[14] R. H. Clarke, "A statistical theory of mobile-radio reception," *Bell System Technical Journal*, vol. 47, pp. 957–1000, 1968.

[15] "Guidelines for evaluations of radio transmission technologies for IMT-2000," ITU ITU-R, Tech. Rep. M.1225, 1997.

[16] "Effective SIR computation for OFDM system-level simulations," 3GPP-TSG-RAN-1, Tech. Rep. RI-03-1370, 2003.

[17] "Technical and operational requirements for the possible operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz," European Communication Committee, Tech. Rep. ECC Report 159, Jan. 2011.

Paper H
Analysis Framework for Opportunistic Spectrum OFDMA and its Application to IEEE 802.22 Standard

Jihoon Park, Przemysław Pawełczak, Pål Grønsund and Danijela Čabrić

IEEE Transactions on Vehicular Technology, vol. 61, no. 5, pp. 2271-2293, Jun. 2012.

Analysis Framework for Opportunistic Spectrum OFDMA and Its Application to the IEEE 802.22 Standard

Jihoon Park, Przemysław Pawełczak, *Member, IEEE*, Pål Grønsund, and Danijela Cabric

***Abstract*—We present an analytical model that enables the evaluation of opportunistic spectrum orthogonal frequency division multiple-access (OS-OFDMA) networks using metrics such as blocking probability or, most importantly, throughput. The core feature of the model, based on a discrete-time Markov chain, is the consideration of different channel and subchannel allocation strategies under different primary and secondary user types, traffic, and priority levels. The analytical model also assesses the impact of different spectrum sensing strategies on the throughput of OS-OFDMA network. In addition, we consider studies of cochannel interference. The analysis is applied to the IEEE 802.22 standard to evaluate the impact of the two-stage spectrum sensing strategy and the varying temporal activity of wireless microphones on the system throughput. In addition to the analytical model, we present a set of comprehensive simulation results using NS-2 related to the delay performance of the OS-OFDMA system considered. Our study suggests that OS-OFDMA with subchannel notching and channel bonding could provide almost ten times higher throughput compared with a design without these options when the activity and density of wireless microphones are very high. Furthermore, we confirm that OS-OFDMA implementation without subchannel notching, which is used in the IEEE 802.22, can support the real-time and non-real-time quality of service classes, provided that the temporal activity of wireless microphones is moderate (with sparse wireless microphone distribution, with light urban population density and short duty cycles). Finally, the two-stage spectrum sensing option improves the OS-OFDMA throughput, provided that the length of spectrum sensing at every stage is optimized using our model.**

***Index Terms*—Cognitive radio, dynamic spectrum access, IEEE 802.22, medium access control (MAC), wireless microphones (WMs).**

Manuscript received April 2, 2011; revised December 14, 2011; accepted January 14, 2012. Date of publication February 22, 2012; date of current version June 12, 2012. This paper has been presented in part at the IEEE Global Communications Conference, Miami, FL, December 2010. The review of this paper was coordinated by Prof. H.-H. Chen.

J. Park was with the Department of Electrical Engineering, University of California, Los Angeles, Los Angeles, CA 90095-1594 USA. He is now with the Mobile Communication Division, Samsung Electronics Company, Gyeonggi-do 443-742, Korea (e-mail: jpark0@samsung.com).

P. Pawełczak was with the Department of Electrical Engineering, University of California, Los Angeles, CA 90095-1594 USA. He is now with the Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, 10587 Berlin, Germany (e-mail: przemyslaw.pawelczak@hhi.fraunhofer.de).

P. Grønsund is with Telenor, 1331 Fornebu, Norway, with Simula Research Laboratory, 1364 Fornebu, Norway, and also with the Department of Informatics, University of Oslo, 0373 Oslo, Norway (e-mail: paalrgr@ifi.uio.no).

D. Cabric is with the Department of Electrical Engineering, University of California, Los Angeles, CA 90095-1594 USA (e-mail: danijela@ee.ucla.edu).

Digital Object Identifier 10.1109/TVT.2012.2188550

I. Introduction

ONE OF the ways to combat artificial spectrum scarcity is to augment existing radio access techniques with opportunistic spectrum access (OSA) [2], [3]. Wireless networks with OSA capabilities can search for unused licensed portions of the radio spectrum and communicate over those vacant radio frequencies whenever available radio capacity is insufficient while meeting the required interference constraints.

Orthogonal frequency division multiple access (OFDMA) is a multiple access technique where orthogonally divided frequency subcarriers are assigned to individual users of the network. A subcarrier assignment is usually performed by a central entity, often the base station (BS), and can be based on the quality of service (QoS) requirements of the individual users. Because of high spectral efficiency, as well as robustness to intersymbol interference, OFDMA was a design choice of recent wireless networking standards, e.g., the IEEE 802.16, the IEEE 802.20, and Third-Generation Partnership Project (3GPP) Long Term Evolution. Because opportunistic spectrum use can efficiently be implemented with OFDMA, it seemed natural to connect the strengths of OFDMA with the flexibility of OSA. The first paper that introduced such concept, denoted in the remainder of this paper as opportunistic spectrum orthogonal frequency division multiple access (OS-OFDMA), was [4], where the approach was referred to as spectrum pooling and OFDM subcarriers that were assigned to individual OSA users [denoted as secondary users (SUs)] are deactivated whenever the primary user (PU) of the radio frequency band reappears.

So far, no theoretical work on the system-level and cross-layer performance of OS-OFDMA networks has been reported. The need for a theoretical framework for OS-OFDMA is also motivated by the recent introduction of the OSA network standard IEEE 802.22 [5]. The IEEE 802.22, an extension of the IEEE 802.16 standard, is designed to operate in the vacant television (TV) bands.[1]

Our goal is to develop the analytical framework to analyze the impact of the traffic characteristics of OS-OFDMA network subscribers, the activity of the PUs of the radio spectrum,

[1]Note that the IEEE 802.22 is not the only networking standard proposed that focused on the operation in the TV white spaces. The remaining standards are the recently published European Computer Manufacturers Association (ECMA) TC48-TG1 standard, which focuses on porting local area networks to TV white spaces, and the recently started IEEE 802.11af, which is similar in scope to the aforementioned ECMA activity.

and the spectrum sensing algorithm and OFDM subcarrier assignment algorithm on the average blocking probability and throughput of an OS-OFDMA network. Our approach is based on a cross-layer Markov-chain-based analysis of OS-OFDMA, which allows the investigation of interactions between the medium access control (MAC) and spectrum sensing layers. Because many options of OS-OFDMA subcarrier and subchannel assignment algorithms exist (i.e., noncontinuous subchannel assignment, as advocated in [4], and a continuous version, as used in the IEEE 802.22 [5]), it is important to compare these designs using a common analytical framework. In addition, the analysis of a two-stage spectrum sensing algorithm, proposed by the IEEE 802.22 standard, is challenging due to its complex effect on the MAC layer and has not been explored in the context of OS-OFDMA communication. Finally, in the context of the IEEE 802.22, analysis could provide estimates of what QoS classes can be supported in OS-OFDMA, given realistic network conditions, such as the number and type of PUs, the number and type of QoS classes enabled by OS-OFDMA network, and the priority order in channel access for each class of users. As an extension to the analytical model, we also present a set of extensive simulation results using NS-2 [6] related to the delay performance of the OS-OFDMA system considered.

The rest of this paper is organized as follows. Work relevant to the objective of this paper is reviewed in Section II. The system model that describes OS-OFDMA network design options in detail is presented in Section III. The analytical model for evaluating the throughput and blocking probability of the system considered is presented in Section IV. Numerical results follow in Section V. Finally, this paper is concluded in Section VI.

II. Related Work

In [7], a general framework of the IEEE 802.16 with OSA capabilities has been proposed with a very simplified networking model based on the Erlang-B formula [7, Sec. V-A], where the focus of the paper has mostly been on propagation calculations, including coverage, interference, and protection distances. In [8], a simulation platform for the IEEE-802.22-like network, with a limited set of ODFMA design options, has been presented. Focusing on the IEEE 802.22, interestingly, although many papers analyzed a certain functionality of the IEEE 802.22 network, such as efficient spectrum sensing algorithm design [9], [10], circuit design for dedicated spectrum sensing [11], MIMO extensions for the IEEE 802.22 physical (PHY) layer [12], game-theoretic analysis of the IEEE 802.22 networks coexistence [13], duplexing schemes [14], and mesh establishment [15], it is desirable to develop a unifying model that captures the IEEE 802.22 intrinsic features such as multiple classes of traffic, two-stage spectrum sensing, different types of PUs and their temporal activity, and the OFDMA subcarrier allocation process.

The work that is closest to the scope of this paper can be found in [16], in which the IEEE 802.16 system was evaluated. Obviously, the model that was developed therein cannot directly be used to evaluate the OS-OFDMA system due to the lack of spectrum sensing and PU activity features. A work similar to ours, analyzing the system-level aspects of subchannel/subcarrier allocation strategies for OS-OFDMA, has been presented in [17]. However, no comparison with the IEEE 802.22 subchannel assignment has been considered. Furthermore, no QoS classes, PU priorities, and two-stage spectrum sensing mechanisms were included in the model. Finally, we need to mention a set of papers that analyze the performance of MAC protocols for OSA networks. Some of the relevant papers include [18]–[20]; however, none of these works consider OFDMA, usually abstracting underlying physical channel structure.

In this paper, we propose an analytical framework to quantitatively assess the performance of a network based on OS-OFDMA, considering features such as channelization structure, subcarrier allocation, resource assignment to network subscribers, and different spectrum sensing methods. In the model, we consider different priorities and channel dwell times of the SUs and PUs of the spectrum. The model developed allows us to calculate capacity (measured in terms of the average throughput) for real-time and non-real-time QoS classes of the OS-OFDMA network. The model also considers the blocking probability for a real-time QoS class.

III. System Model

We consider a centrally controlled network that employs OS-OFDMA, where a BS manages resources and coordinates the spectrum sensing of individual OS-OFDMA network subscribers. For simplicity, we assume that only downlink traffic is transmitted. In this paper, we assume a single-cell configuration with multiple SUs and multiple PUs, belonging to different user classes. This condition allows the exclusion of the effect of cochannel interference, as well as coexistence mechanisms in the OSA network, on the investigation of the relation between PU type, its activity level, and OS-OFDMA design options.[2] On the other hand, we consider transmission errors due to fading and noise on the subchannels. Although we assume that OS-OFDMA users cause no harmful interference to the neighboring PU throughout most of this paper, in the numerical studies, we will also consider a simple study on the effect of the adjacent channel interference on PU detection performance.

We identify the following two main modules of our system model: 1) data transmission, which is responsible for regular data communication between SUs, and 2) spectrum sensing, which is responsible for the efficient detection of spectrum opportunities for the OSA network; see also [20] for a similar model. Each component has its unique PHY and MAC layers. Obviously, each layer has its unique design options, e.g., channel and subchannel management algorithms and multistage

[2]Note that the unique feature of the IEEE 802.22 network, which our analytical framework specifically targets, is the ability to share resources between multiple coexisting networks through a coexistence protocol [21]. In the extreme case when there are no x unique channels available for x collocated IEEE 802.22 networks, all BSs employ a adaptive duplexing mechanism, called an upstream/downstream split [5, Sec. 6.14.1], in which frames are shared between all coexisting networks in a time-domain basis. Due to this mechanism, cochannel and adjacent channel interference due to neighboring cells do not contribute to the degradation of the network performance. Therefore, calculations of cochannel interference, which are certainly applicable to IEEE 802.16 and presented in [16, Sec. II], are not necessary in the case of our analysis.

TABLE I
SUMMARY OF SYMBOLS USED IN THIS PAPER

Variable	Description	Unit
b, θ, γ, $\gamma(i)$	Subchannel bandwidth, sensing threshold, PU signal SNR, PU signal SNR at SU i	Hz, —, dB, dB
w, n, c, v, a (f)	Index: WPU, NPU, CBR, VBR, coarse (fine) sensing	—
x, y, i, j, k, r	Supporting variables	—
$1/h$, v	Number of inhabitants per active NPU, user speed	—, mph
m_x (l_x)	Number of subchannels used by (assigned to) user x	—
t_f	Frame length	s
t, $x^{(t)}$	Time stamp, variable x at time t	—
C, C_p	Throughput: subchannel, MAC layer subchannel	bps
H, H_x	Throughput: total, obtained by connection type x	—
M, M_e	Number of subchannels: total, detected as idle	—
M_m, M_p, M_0	Number of subchannels: mis-detected, used by PU, detected as idle	—
X, X_n, X_a	Number of channels: total, used by PU, detected as idle	—
U_x, $U_{x,\max}$	Number of users: type x, type x maximum	—
U_e	Number of CBR users able to utilize all subchannels	—
U_{μ_x}	Supporting variable to calculate $T_x(\cdot)$	—
U_{e1}, U_{e2}	Supporting variables denoting number of subchannels available to NPUs	—
Y	Number of subchannels per channel	—
S	Two-stage sensing option indicator	—
F, V	Supporting variable to calculate: $\mathrm{Pr}_{14}(\cdot)$, $\mathrm{Pr}_{25c}(\cdot)$	—
L	BS cell diameter	mi
1_c	Indicator function for feasible conditions of $\mathrm{Pr}_{20}(\cdot)$	—
p_{10}, $p_{10}^{(i)}$, p_{11}	Probability for single SU node: false alarm, false alarm at SU i, detection,	—
$\mathrm{Pr}_x(\cdot)$	Expressions to calculate average throughput	—
R_B	CBR blocking probability	—
Pr_B, Pr_b, Pr_{b+}, Pr_c	Supporting functions to caclulate R_B	—
$\tau_{a,r}$, $\tau_{f,r}$	Minimum required coarse and fine sensing time, respectively	s
$\phi_{a,r}$, $\delta_{a,r}$	Minimum required coarse probability of false alarm, probability of detection, respectively	—
$H_{c,r}$, $H_{v,r}$	Minimum required throughput for CBR and VBR class, respectively	bps
$f_+(\cdot)$, $f_s(\cdot)$	Supporting function to calculate: $\mathrm{Pr}_2(\cdot)$, $\mathrm{Pr}_{21}(\cdot)$	—
H, $J^{(y)}$	Supporting function to calculate: $\mathrm{Pr}_{25}(\cdot)$, $\mathrm{Pr}_{25x}(\cdot)$	—
$G_x(\cdot)$, $T_x(\cdot)$	Probability: connection generation, connection termination (type x)	—
$\mathcal{K}_{c,a}$, $\mathcal{K}_{c,b}$, $(\mathcal{K}_v)$	Vectors of possible i, j for $U_c^{(t)}$ $(U_v^{(t)})$	—
$\mathcal{K}_{n,a}$, $\mathcal{K}_{n,b}$, $(\mathcal{K}_w)$	Vectors of possible i, j for $U_n^{(t)}$ $(U_w^{(t)})$	—
$\mathcal{M}, \mathcal{U}, \mathcal{U}_m, \mathcal{S}$	Sets: $\{U_c, U_v, M_e\}$, $\{U_w, U_n\}$, $\{U_{c,\max}, U_{v,\max}\}$, $\{S, U_w, U_n\}$	—
$\mathcal{X}$, $\mathcal{Y}$, $\mathcal{Z}$	Sets: $\{X_n\}$, $\{0, \ldots, M\}$, $\{Y, \ldots, M\}$	—
$\mathcal{W}$	Set of all possible values of $U_c^{(t)}$, $U_c^{(t-1)}$, $M_a^{(t)}$ and $M_a^{(t-1)}$	—
$\mathcal{I}(\cdot)$	Supporting set to calculate $f_s(\cdot)$	—
$1/\lambda_x$, $1/\mu_x$	Average time: departure, arrival (type x)	s
δ_x, ϕ_x (τ_x)	Probability: false alarm, detection (sensing) time (stage x)	—
ξ, η	MAC overhead, average ratio of data transmission to total frame length	—
ρ	Population density	—
$\mathbb{N}$, $\mathbb{R}$	Number sets: natural, real	—

sensing. In addition, the OSA network can be described by individual parameters such as the type of traffic, activity level, and bandwidth used. We aim at calculating the average throughput that was obtained at the data MAC layer for all classes of SU traffic, which will be described in detail in Section III-A2. We also aim at calculating blocking probability for a real-time QoS class of the OS-OFDMA network.

A. OSA System Configuration

1) Channel Setup and Its Relation to OFDMA: The frequency domain consists of X channels, each of which is composed of Y OFDMA subchannels of bandwidth b. The total number of subchannels is thus $M = XY$ (note that all variables that were used in the paper are summarized in Table I). Each subchannel is further composed of OFDM subcarriers. In this paper, we constrain the analysis to the subchannel domain. Furthermore, we assume that the subchannel throughput C is, on the average, constant, whereas its average value depends on the PHY-layer characteristics such as modulation, error control coding, and MAC-layer overhead such as the OFDMA preamble length.

In the time domain, transmission segments are divided into frames of length t_f. At the beginning of each frame, SUs of OSA network detect the presence of the PU. We implicitly assume synchrony between PU and SU activity, because it is a well-established classical assumption in the theoretical analysis; for example, see recent publications [20], [22, Fig. 2], [23, Fig. 1], [24, Fig. 2], [17], and [25]–[27] that follow the same path. Note, however, that the proposed model is extendable to the case where PU slots are offset in time from SU slots. This would require further analysis of PU channel access policies [28], [29], which is beyond the scope of this paper. We emphasize, as shown in [20], [30], and [31], that the assumption about the synchrony between PU and SU connections allows us to calculate throughput and blocking probability upper bounds compared to transmission on a slot-asynchronous interface.[3]

[3]For the first analysis of the OSA network with asynchronous PU/SU interface, see [32].

Furthermore, we assume that each node in the OSA network observes the same signal that was emitted by the PU; thus, each SU individually performs all the sensing measurements and sends the measurement result to BS on the uplink. Then, the BS makes a final decision about the presence of a PU on each subchannel.

2) PU and SU Types: We consider different types of PUs and SUs. For the PUs, depending on the bandwidth and the activity level, we classify them into the following types: 1) a wideband primary user (WPU) with low activity, i.e., with long busy and long idle times, and 2) a narrowband primary user (NPU) with high activity, i.e., with short busy and shorter than WPU idle times. This classification makes the analysis more detailed and realistic. It also makes different scenarios of interest possible to analyze. For example, the WPU can represent wireless video links, whereas the NPU can represent wireless microphones (WMs), both operating in the TV bands. For SUs, again making our framework general and applicable to multiple scenarios, we consider the following two types of users: 1) users who receive real-time traffic, denoted as the constant bit rate (CBR) SUs, and 2) users who receive elastic traffic, denoted as variable bit rate (VBR) SUs, which are included in the IEEE 802.22 standard. In our OSA network model, different types of SU traffic flows are generated at the upper layers, i.e., application, network, and transport, and forwarded down to data PHY, whereas PU signals are detected at the spectrum sensing module.

Furthermore, we assume that a hierarchical structure of users is present such that the WPU has the highest priority in accessing bandwidth, the NPU is the second in access hierarchy, followed by CBR and, finally, VBR. In other words, if users of different classes could access the same subchannel, the lower priority class user must vacate for the higher priority class user to utilize the subchannel. The evacuated CBR switches to the other idle subchannels or drops the connection if there is no idle subchannel available. For VBR, if the PU is detected, the active VBR connection squeezes the bandwidth [16, Sec. III-B], excluding the channel or subchannel occupied by the PU, and if there is no channel that is detected as idle, it buffers data until the PU disappears. Note that the behavior of VBR promises to obtain the highest possible throughput, as demonstrated in [20, Sec. V-B and Fig. 6], assuming no switching overhead, whereas CBR does not consider buffering due to the excessive delay that this class might experience while waiting for the WPU or NPU to vacate the bandwidth.

Because of the finite channel capacity, the number of users considered in the system is finite, but different for different user types. We assume that at most $U_{w,\max}$, $U_{n,\max}$, $U_{c,\max}$, and $U_{v,\max}$ of the WPU, NPU, CBR, and VBR connections, respectively, can be active at the same time in the considered bandwidth [16, Sec. III-B]. For the data traffic of SUs and PUs, for analytical tractability, we assume that all users generate new connections according to the negative exponential distribution for the interarrival time and burst departure time, which is again a classical assumption in performance analysis studies [33]. The analysis can be extended to the general distributions of PU and SU traffic, which is beyond the scope of this paper. Note, however, that the recent measurement campaign [34] showed that more than 60% of the measured PU activities distributions, including industrial, scientific, and medical (ISM) and cellular bands, fit an exponential distribution. The average interarrival and departure time are denoted, respectively, as $1/\lambda_w$ and $1/\mu_w$ for WPU, $1/\lambda_n$ and $1/\mu_n$ for NPU, $1/\lambda_c$ and $1/\mu_c$ for CBR, and $1/\lambda_v$ and $1/\mu_v$ for VBR. In addition, we assume that the connection of each class, except for VBR, occupies a fixed number of subchannels. We denote the instantaneous number of subchannels that were utilized by a connection class as l_w for WPU, l_n for NPU, l_c for CBR, and l_v for VBR. Note that the number of subchannels assigned to every connection is fixed and that l_c, l_w, $l_n \in \mathbb{N}$, except for a VBR connection. In that case, $l_v \in \mathbb{R}$, which stems from the fact that one data frame consists of a group of OFDMA symbols and the symbols in the OFDMA frame can be assigned to multiple VBR connections. In addition, for VBR connections, the burst departure time depends on the number of subchannels used by VBR; thus, $1/\mu_v$ is an average departure time when one subchannel is assigned to the VBR connection.

B. Design Options

1) Spectrum Sensing PHY and MAC Layers: The spectrum sensing PHY senses the PU signal and passes the measurement about subchannel availability to the sensing MAC layer for further processing. The main parameters for the spectrum sensing PHY are the probability of detection, the probability of false alarm, and the sensing time.

In the sensing MAC layer, the SUs collectively decide, with the help of the BS, on the PU state on the subchannel based on the sensing results of the sensing PHY layer. We denote the detection based on multiple users as cooperative sensing and the detection based on multiple periods as multistage sensing. Because the performance of cooperative sensing is relatively well known (for example, see [20]), in this paper, we focus our analysis mostly on multistage sensing. For the first results related to multistage spectrum sensing in network context, refer to [35]–[37] for two-stage sensing multichannel systems and to [38] for a two-stage sensing single channel system.

In this paper, we are limited to two-stage sensing, noting that our analysis can directly be extended to multistage sensing. The procedure works as follows. First, the SU coarsely senses the subchannel at the beginning of every frame, with short sensing time and low sensing accuracy. If the PU is detected, the SU switches to fine sensing mode (immediately, in the same frame), with long sensing time and high sensing accuracy. Depending on the sensing strategy, fine sensing can increase the sensing accuracy [38] or frequency resolution [35]. Two-stage sensing can be described by different sensing PHY parameters for each stage. We denote the system-wide probability of detection as δ_a and δ_f, the probability of false alarm as ϕ_a and ϕ_f, and the sensing time as τ_a and τ_f for coarse and fine sensing stages, respectively. In this paper, we assume that global probabilities of detection and false alarm at the coarse sensing phase are the function of individual detection probabilities for each SU, i.e., false-alarm probability p_{10} and detection probability p_{11}, which are assumed to be, on the average, the same for each sensing SU. Probabilities p_{10} and p_{11} are a function of sensing bandwidth b, sensing threshold θ, and the PU signal level observed by the SU at its sensor γ [20]. Sensing results are fused by the BS based on a predefined fusion rule, whereas the model of cooperative spectrum sensing used in this paper will be given in Section V-D. Furthermore, for simplicity, we assume that the fine-sensing phase is performed only by the BS. When setting $\phi_a = 1$ and $\tau_a = 0$, the two-stage sensing model reduces to a single-stage sensing model.[4]

To evaluate the effect of spectrum sensing on the system throughput and blocking probability, we consider two unique sensing strategies. First, we consider a sensing strategy where the SU senses all channels, including the operating channel, with coarse sensing, and when the SU detects the PU on any of the channels, it immediately switches to fine sensing. We call this strategy general two-stage sensing and denote it as S_0.

Second, for a specific case when the bandwidth to transmit data is fixed and less than the whole allowed bandwidth, we investigate the following strategy. During coarse sensing, the SU senses not the whole bandwidth but only a fixed bandwidth that is currently utilized for data transmission. If the PU is detected on the channel, the SU immediately senses all channels allowed to be utilized for the OSA system with fine sensing and switches to one of the channels detected as idle. We call this strategy two-stage active channel sensing and denote it as S_1. Because, in this strategy, contrary to S_0, there is no need to always sense all channels, the sensing time is reduced.

2) Data PHY and MAC Layers: Although the OSA network is aware that subchannels are idle or busy, it should determine how to utilize the subchannels detected as idle for data transmission. First, we need to determine how much bandwidth is utilized for data transmission from the channels detected as idle. One strategy is to utilize all channels detected as idle from the allowed bandwidth. This strategy may maximize channel utilization at the cost of the wideband RF and signal processing.[5] We call this strategy variable channel/subchannel bonding and denote it as B_1. On the other hand, another strategy is to transmit data through only one channel, although there may exist more channels detected as idle. Because the SU operates on the bandwidth of only one channel, the cost for the RF and signal processing is low. However, this is inefficient, because some available bandwidth may not be utilized. Because it is one of the operating modes of the IEEE 802.22, which is also advocated by the Federal Communications Commission [43], we also include it in this paper. We call this strategy fixed channel selection and symbolically denote it as B_0.

Second, we also include a strategy to avoid utilizing the subchannels on which the PU is detected. One efficient strategy is to notch out the subchannel detected as busy and utilize all other available subchannels for OS-OFDMA. We call this strategy subchannel notching and denote it as N_1. Note that we assume, for simplicity, that it is possible to notch out subchannels and transmit on the adjacent subchannels without causing interference, which is a common assumption in system-level analysis, e.g., [17] and [25].[6] On the contrary, a conservative strategy is to exclude (block) all subchannels within the operating channel from accessing, although only one subchannel is utilized by the PU, which is suggested for the IEEE 802.22. We call this strategy channel blocking and symbolically denote it as N_0.

Note that the channel switching delay is on the order of tens to hundreds of microseconds [47], [48], which is a fraction of the channel sensing time. Depending on the protocol design, an additional OFDMA frame might be needed to communicate the decision about channel switch between the BS and terminals. For simplicity, the channel switching delay is neglected in the analysis.

3) Design Options of Interest: Because we have three groups of binary choices, i.e., S_x, N_x, and B_x, where $x \in \{0, 1\}$, there can be eight possible combinations of design options. However, not all options are feasible. First, we do not consider the combination of subchannel notching (N_1) and fixed channel selection (B_0), because it is a special case of $\mathrm{N}_1\mathrm{B}_1$ configuration with a single channel. In addition, for two-stage active channel sensing (S_1), we consider only channel blocking (N_0) and fixed channel selection (B_0), because two-stage active channel sensing (S_1) is applicable to the fixed bandwidth utilization case only. This leaves four combinations of the design options. Note that all options, except for $\mathrm{S}_0\mathrm{N}_1\mathrm{B}_1$, are considered by the IEEE 802.22 standard.

IV. Proposed Analytical Model

In this section, we will describe the calculation of the average throughput and blocking probability obtained using each of the OS-OFDMA designs considered. The analysis is based on a probabilistic framework utilizing Markov chain. We begin with throughput calculation as a blocking probability (presented in Section IV-E), which will partially be obtained from the results on the average throughput. We start with the $\mathrm{S}_0\mathrm{N}_1\mathrm{B}_1$ option, which serves as a foundation for analyzing the remaining three OS-OFDMA designs.

A. Case $S_0N_1B_1$: General Sensing, Subchannel Notching, and Subchannel Bonding

In general, in OFDMA-based wireless networks, the throughput depends on how many subchannels are utilized in the idle spectrum by each SU connection type [16, Sec. III-B] (in our model, by every CBR and VBR connection). Let $\mathrm{Pr}_1(m_c, m_v, M_e)$ be the probability that m_c and m_v

[4] In Section V-D, we will compare the performance of two-stage spectrum sensing to single-stage sensing.

[5] Note that the total number of channels that the user of IEEE 802.22 network requires is rather limited in practice, e.g., $X \lessapprox 4$. Therefore, the sufficient number of radio interfaces for IEEE 802.22 does not exceed a typical number of radio interfaces in contemporary wireless mobile devices produced for the mass market. In addition, note that efficient methods of low-complexity wideband spectrum sensing have recently been discussed and proposed in [39]–[42] and can be realized with low-cost radio front ends.

[6] See recent studies on that topic that prove the feasibility of such an approach. For example, in [44], a sidelobe suppression with a guard band equal to only one OFDM subcarrier interval was shown. In [45], an OFDM subcarrier notching was proposed, with only 4% of the available spectrum wastage. Finally, a practical implementation of OFDM subcarrier suppression with perfect channel utilization, at the cost of throughput reduction, was demonstrated in [46]. On the other hand, to relax this assumption, in Section V-E, we will perform a simple evaluation of the considered system model with adjacent channel interference in the context of PU detection.

subchannels are utilized by CBR and VBR connections, respectively,[7] when M_e subchannels are detected as idle. In addition, let $\eta(M_e)$ be the average ratio of data transmission time to total frame length when M_e subchannels are detected as idle. Then, the total system throughput H can be calculated as

$$H \triangleq C \sum_{M_e=0}^{M} \eta(M_e) \sum_{m_c, m_v \in \{0,\ldots,M\}} (m_c + m_v) \mathrm{Pr}_1(m_c, m_v, M_e). \tag{1}$$

In addition, the throughput of CBR connection H_c and VBR connection H_v is calculated using (1) by replacing $m_c + m_v$ with m_c for H_c and m_v for H_v. In the following sections, we will describe a method of deriving $\mathrm{Pr}_1(\cdot)$ and $\eta(\cdot)$. In this method, we will hierarchically decompose $\mathrm{Pr}_1(\cdot)$ and $\eta(\cdot)$ into a set of conditional probabilities. Each probability will describe a particular relation between the spectrum sensing outcome, the state of CBR and VBR connections, and the PU activity.

1) Derivation of the Probability of the Number of CBR and VBR Connections and Available Subchannels $\mathrm{Pr}_1(\cdot)$*:* Values of m_c and m_v are easily determined if we know the number of CBR connections that are connected with the BS U_c, the number of VBR connections that are connected with the BS U_v, and the number of subchannels that are detected as idle M_e. Thus

$$\mathrm{Pr}_1(\cdot) \triangleq \sum_{U_c=0}^{U_{c,\max}} \sum_{U_v=0}^{U_{v,\max}} \mathrm{Pr}_2(m_c, m_v | U_c, U_v, M_e) \times \mathrm{Pr}_3(U_c, U_v, M_e), \tag{2}$$

where $\mathrm{Pr}_2(\cdot)$ denotes a set of allowed subchannel configurations that are occupied by CBR and VBR connections, and $\mathrm{Pr}_3(\cdot)$ denotes the probability of active U_c CBR connections, U_v VBR connections, and M_e idle subchannels.

a) Derivation of the allowed CBR and VBR subchannel configurations $\mathrm{Pr}_2(\cdot)$*:* Because the total number of subchannels used by all CBR users $U_c l_c$ cannot be greater than the number of available subchannels M_e, because if there is no subchannel available, the CBR connection will be blocked, the only valid case is $U_c l_c \le M_e$. Furthermore, if a CBR connection has a higher priority than a VBR connection, all CBR connections can transmit data through all $m_c = U_c l_c$ subchannels. Then, the remaining subchannels, i.e., $m_v = M_e - U_c l_c$, are used by VBR connections. On the other hand, if there are no VBR connections in the system, then $m_v = 0$. Therefore, defining $\mathbb{U}(x)$, where $\mathbb{U}(x \le 0) = 0$, and $\mathbb{U}(x > 0) = 1$, we have

$$\mathrm{Pr}_2(\cdot) \triangleq \begin{cases} 1, & U_c l_c \le M_e, m_c = U_c l_c \\ & m_v = (M_e - U_c l_c)\mathbb{U}(U_v), \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

b) Derivation of the probability of active CBR and VBR connections and idle subchannels $\mathrm{Pr}_3(\cdot)$*:* Because our model considers the arrival process of SU connections, the departure process of which is affected by the PU temporal activity, to calculate $\mathrm{Pr}_3(\cdot)$ in (2), we need a tool for evaluating the steady-state probability of given number of CBR and VBR connections, as well as the number of idle subchannels. To do this, we use a widely adopted method based on the composition of a Markov chain [33, Ch. 11].

We introduce a Markov chain state $\{U_c, U_v, M_e\}$, where the state space of this Markov chain is given as $\forall U_c$, U_v, M_e, M such that $U_c + U_v + M_e \le M$. Furthermore, we introduce the state transition probability, which describes the change in $\{U_c, U_v, M_e\}$ between time $t-1$ and t, and is denoted as $\mathrm{Pr}_4(U_c^{(t)}, U_v^{(t)}, M_a^{(t)} | U_c^{(t-1)}, U_v^{(t-1)}, M_a^{(t-1)})$. Then, we can calculate $\mathrm{Pr}_3(\cdot)$ by solving the Markov chain, given $\sum_{\mathcal{M}} \mathrm{Pr}_3(\cdot) = 1$ and $\mathrm{Pr}_3(\cdot) = \sum_{\mathcal{M}^{(t-1)}} \mathrm{Pr}_3(\cdot)\,\mathrm{Pr}_4(\cdot)$, where $\mathcal{M}$ is a set of all possible states $\{U_c, U_v, M_e\}$, and $\mathcal{M}^{(x)}$ is a set of the states at time x. Based on the conditional probability property and the independence of the variables, we decompose $\mathrm{Pr}_4(\cdot)$ as

$$\mathrm{Pr}_4(\cdot) \triangleq \mathrm{Pr}_5\left(U_c^{(t)}, U_v^{(t)} | U_c^{(t-1)}, U_v^{(t-1)}, M_a^{(t)}, M_a^{(t-1)}\right) \times \mathrm{Pr}_6\left(M_a^{(t)} | M_a^{(t-1)}\right), \tag{4}$$

where $\mathrm{Pr}_5(\cdot)$ denotes the probability of change in the number of CBR and VBR connection counts, and $\mathrm{Pr}_6(\cdot)$ denotes the probability of change in the number of subchannels detected as idle. We derive these expressions as follows.

c) Derivation of the probability of change in CBR and VBR connection counts $\mathrm{Pr}_5(\cdot)$*:* We can decompose $\mathrm{Pr}_5(\cdot)$ into probabilities that separately denote a change in the number of connections for CBR and VBR. Accordingly, we define $\mathrm{Pr}_7(U_c^{(t)} | U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)})$ as the conditional probability of the number of the CBRs at time t for the given number of subchannels detected as idle and $\mathrm{Pr}_8(U_v^{(t)} | U_v^{(t-1)}, U_c^{(t)}, U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)})$ as the conditional probability of the number of VBR connections at time t for the given number of CBR connections and the available subchannels. Note that, in $\mathrm{Pr}_7(\cdot)$, because we assume that the CBR has higher priority than the VBR and the VBR connections utilize the remaining subchannels after subchannel assignment for all CBR connections, there is no dependence on $U_v^{(t-1)}$. Furthermore, note that the $\mathrm{Pr}_7(\cdot)$ and $\mathrm{Pr}_8(\cdot)$ change in the number of CBR and VBR connections, respectively, depends on the number of subchannels detected as idle at time $t-1$ and t. Then, we have

$$\mathrm{Pr}_5(\cdot) \triangleq \mathrm{Pr}_8\left(U_v^{(t)} | U_v^{(t-1)}, U_c^{(t)}, U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)}\right) \times \mathrm{Pr}_7\left(U_c^{(t)} | U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)}\right). \tag{5}$$

We proceed with describing the process of deriving the expressions for $\mathrm{Pr}_7(\cdot)$ and $\mathrm{Pr}_8(\cdot)$.

d) Derivation of the probability of change in the CBR connection count $\mathrm{Pr}_7(\cdot)$*:* First, we consider valid conditions for $U_c^{(t)}$, $U_c^{(t-1)}$, $M_a^{(t)}$, and $M_a^{(t-1)}$ for $\mathrm{Pr}_7(\cdot)$ involving all possible numbers of i arriving and j departing connections. We denote the number of users that can utilize all available subchannels as $U_a^{(t)} = \lfloor M_a^{(t)}/l_c \rfloor$ at time t and $U_a^{(t-1)} = \lfloor M_a^{(t-1)}/l_c \rfloor$ at time $t-1$. Then, because $U_a^{(t)}$, $U_a^{(t-1)}$ denote the maximum number of users $U_c^{(t)} \le U_a^{(t)}$ and

[7]In this paper, we follow the convention that each newly introduced probability will uniquely be identified by a number and introduced with all argument variables, whereas its later callouts will be referred to as $\mathrm{Pr}_x(\cdot)$.

$U_c^{(t-1)} \leq U_a^{(t-1)}$. Furthermore, because the possible sets of i and j are different for the cases $U_c^{(t)} < U_a^{(t)}$, $U_c^{(t)} = U_a^{(t)} > 0$, and $U_c^{(t)} = U_a^{(t)} = 0$, we separately consider them.

The first case, $U_c^{(t)} < U_a^{(t)}$, represents the situation when the number of subchannels detected as idle is more than the number of all subchannels that will be utilized by CBR connections before spectrum sensing. In other words, no CBR connection is blocked due to the PU appearance. Because the numbers of CBR connections are $U_c^{(t-1)}$ at time $t-1$ and $U_c^{(t)}$ at time t, the change in the number of CBR connections is $i - j = U_c^{(t)} - U_c^{(t-1)}$. In addition, because there are $U_c^{(t-1)}$ active connections at time $t-1$, more than $U_c^{(t-1)}$ connections cannot be released, i.e., $j \leq U_c^{(t-1)}$. Therefore, $\{i, j\} \in \mathcal{K}_{c,a} \triangleq \{i, j | i - j = U_c^{(t)} - U_c^{(t-1)}, j \leq U_c^{(t-1)}\}$.

The second case, $U_c^{(t)} = U_a^{(t)} > 0$, denotes the situation when CBR connections may be blocked due to the PU arrival. Then, before spectrum sensing, the total number of connections, including newly generated connections, is $U_c^{(t-1)} + i - j$. However, after spectrum sensing, the connections that utilize subchannels detected as busy are blocked, and the remaining connections $U_c^{(t)}$ utilize all available subchannels, $M_a^{(t)}$. Thus, the number of CBR connections before spectrum sensing $U_c^{(t-1)} + i - j$ can be greater than or equal to the number of CBR connections after spectrum sensing $U_c^{(t)}$ but should be less than or equal to $U_{c,\max}$, i.e., $U_c^{(t)} \leq U_c^{(t-1)} + i - j \leq U_{c,\max}$. Therefore, $\{i, j\} \in \mathcal{K}_{c,b} \triangleq \{i, j | U_c^{(t)} - U_c^{(t-1)} \leq i - j \leq U_{c,\max} - U_c^{(t-1)}, j \leq U_c^{(t-1)}\}$.

The third and final case is when $U_e^{(t)} = U_c^{(t)} = 0$. In this situation, because no subchannels are available for CBR, the number of CBR connections should also be zero. Consequently, regardless of i and j, the conditional probability $\Pr_7(\cdot)$ under this condition is always one.

Now, we introduce two supporting functions $G_x(i|U_x, \lambda_x)$ and $T_x(j|U_x, \mu_x)$ that will be used to derive $\Pr_7(\cdot)$, where $G_x(i|U_x, \lambda_x)$ is the probability that i connections are newly generated from U_x available users with arrival rate λ_x, and $T_x(j|U_x, \mu_x)$ is the probability that j connections are released, each with departure rate μ_x. $G_x(i|U_x, \lambda_x)$ and $T_x(j|U_x, \mu_x)$ are derived in Appendix A. Our approach to derive $\Pr_7(\cdot)$ is to calculate all possible sets for i and j and apply them to $G_x(i|U_x, \lambda_x)$ and $T_x(j|U_x, \mu_x)$. As a result, $\Pr_7(\cdot)$ is derived as in (6), shown at the bottom of the page.

e) Derivation of the probability of change in the VBR connection count $\Pr_8(\cdot)$*:* In our model, we do not consider the case that the VBR connection is blocked by the PU, because VBR connections are assumed to be buffered instead of blocked when there is no available subchannel. Thus, assuming that all VBR connections share the same portion of the idle bandwidth, we calculate the number of subchannels assigned to one VBR connection l_v as

$$l_v = \begin{cases} \frac{M_a^{(t-1)} - U_c^{(t-1)}}{U_v^{(t-1)}}, & U_v^{(t-1)} > 0, \\ 0, & U_v^{(t-1)} = 0. \end{cases} \tag{7}$$

In turn, $\Pr_8(\cdot)$ based on (5) is similarly defined to (6) as

$$\Pr_8(\cdot) \triangleq \sum_{\{i,j\} \in \mathcal{K}_v} T_v\left(j | U_v^{(t)}, l_v \mu_v\right) G_v\left(i | U_v^{(t-1)}, \lambda_v\right), \tag{8}$$

where $\mathcal{K}_v \triangleq \{i, j | i - j = U_v^{(t)} - U_v^{(t-1)}, j \leq U_v^{(t-1)}\}$.

f) Derivation of the probability of change of the subchannel count detected as idle $\Pr_6(\cdot)$*:* Proceeding to derive $\Pr_6(\cdot)$ in (4), it can be decomposed as

$$\Pr_6(\cdot) \triangleq \frac{\Pr_9\left(M_a^{(t)}, M_a^{(t-1)}\right)}{\Pr_{10}\left(M_a^{(t-1)}\right)}, \tag{9}$$

where $\Pr_9(\cdot)$ denotes the probability that M_e subchannels were detected as idle at times $t-1$ and t, and $\Pr_{10}(\cdot)$ denotes the probability that M_e subchannels were detected as idle at time $t-1$. We will explain the derivation of $\Pr_9(\cdot)$ and $\Pr_{10}(\cdot)$ in the subsequent sections. We have

$$\begin{aligned} \Pr_9(\cdot) \triangleq \sum_{\substack{\forall U_w^{(t)}, U_n^{(t)}, S^{(t)}, \\ U_w^{(t-1)}, U_n^{(t-1)}, S^{(t-1)}}} & \Pr_{11}\Big(M_a^{(t)}, M_a^{(t-1)} | U_w^{(t)}, U_w^{(t-1)}, \\ & U_n^{(t)}, U_n^{(t-1)}, S^{(t)}, S^{(t-1)}\Big) \\ & \times \Pr_{12}\Big(U_w^{(t)}, U_w^{(t-1)}, U_n^{(t)}, U_n^{(t-1)}, S^{(t)}, S^{(t-1)}\Big). \end{aligned} \tag{10}$$

g) Derivation of the probability of M_e number of subchannels detected as idle at times t − 1 and t, $\Pr_9(\cdot)$*:* The idea behind the derivation of (10) is that the number of detected subchannels depends on what sensing stage was utilized at time slots $t-1$ and t and how many NPUs and WPUs were present at these time slots. It can be defined in (11), shown at the bottom of the next page, where $S^{(t)}$ and $S^{(t-1)}$ are the sensing stages at times t and $t-1$, respectively. Furthermore, $\Pr_{11}(M_a^{(t)}, M_a^{(t-1)} | U_w^{(t)}, U_w^{(t-1)}, U_n^{(t)}, U_n^{(t-1)}, S^{(t)}, S^{(t-1)})$ denotes the probability of the number of subchannels detected as idle, given

$$\Pr_7(\cdot) \triangleq \begin{cases} \sum_{\{i,j\} \in \mathcal{K}_{c,a}} T_c\left(j | U_c^{(t)}, \mu_c\right) G_c\left(i | U_c^{(t-1)}, \lambda_c\right), & U_c^{(t-1)} \leq U_a^{(t-1)}, U_c^{(t)} < U_a^{(t)}, \\ \sum_{\{i,j\} \in \mathcal{K}_{c,b}} T_c\left(j | U_c^{(t)}, \mu_c\right) G_c\left(i | U_c^{(t-1)} + i - j, \lambda_c\right), & U_c^{(t-1)} \leq U_a^{(t-1)}, U_c^{(t)} = U_a^{(t)} > 0, \\ 1, & U_c^{(t-1)} \leq U_a^{(t-1)}, U_e^{(t)} = U_c^{(t)} = 0. \end{cases} \tag{6}$$

the number of WPUs and NPUs and the sensing stage at times $t-1$ and t, and $\mathrm{Pr}_{12}(U_w^{(t)}, U_w^{(t-1)}, U_n^{(t)}, U_n^{(t-1)}, S^{(t)}, S^{(t-1)})$ denotes the joint probability of the numbers of WPUs and NPUs and the sensing stage at times $t-1$ and t. We can further decompose $\mathrm{Pr}_{11}(\cdot)$ and $\mathrm{Pr}_{12}(\cdot)$ into subsequent probabilities.

h) Derivation of the probability of the number of subchannels detected as idle, given the number of WPUs and NPUs and the sensing stage at times $t-1$ and t, $\mathrm{Pr}_{11}(\cdot)$: Probability $\mathrm{Pr}_{11}(\cdot)$ in (10) can be decomposed into products of probabilities that describe the available number of subchannels detected as idle at times t and $t-1$, because the number of subchannels detected as idle and the state of the sensing stage at time slot t is independent of time $t-1$, i.e.,

$$\mathrm{Pr}_{11}(\cdot) \triangleq \mathrm{Pr}_{13}\left(M_a^{(t-1)} | U_w^{(t-1)}, U_n^{(t-1)}, S^{(t-1)}\right) \times \mathrm{Pr}_{13}\left(M_a^{(t)} | U_w^{(t)}, U_n^{(t)}, S^{(t)}\right), \quad (12)$$

where $\mathrm{Pr}_{13}(\cdot)$ is derived in Appendix B.

i) Derivation of the probability of the numbers of WPUs and NPUs and the sensing stage at times $t-1$ and t, $\mathrm{Pr}_{12}(\cdot)$: Probability $\mathrm{Pr}_{12}(\cdot)$ in (10) can be decomposed into conditional probabilities as follows:

$$\begin{aligned}\mathrm{Pr}_{12}(\cdot) \triangleq\ & \mathrm{Pr}_{15}\left(S^{(t)} | U_w^{(t)}, U_n^{(t)}\right) \mathrm{Pr}_{15}\left(S^{(t-1)} | U_w^{(t-1)}, U_n^{(t-1)}\right) \\ & \times \mathrm{Pr}_{16}\left(U_w^{(t)}, U_n^{(t)} | U_w^{(t-1)}, U_n^{(t-1)}\right) \\ & \times \mathrm{Pr}_{17}\left(U_w^{(t-1)}, U_n^{(t-1)}\right), \end{aligned} \quad (13)$$

where $\mathrm{Pr}_{15}(\cdot)$ is the probability of being in a certain sensing stage, given the number of NPUs and WPUs, which is derived in Appendix C, and $\mathrm{Pr}_{16}(\cdot)$ and $\mathrm{Pr}_{17}(\cdot)$ are the state transition probability and the steady-state probability for the state $\{U_w, U_n\}$, respectively. As in the case of $\mathrm{Pr}_3(\cdot)$, denoting the probability of the active number of CBR and VBR connections, because the state of NPU and WPU randomly and independently changes from time slot to time slot, we can apply the same method of Markov chain construction to derive the probability of being in any of the $\{U_w, U_n\}$ states, where the state space of this Markov chain is given as $\forall U_w$, U_n, M such that $U_w + U_n \leq M$. We will describe their derivation as follows.

j) Derivation of the steady-state transition probability for state $\{U_w, U_n\}$, $\mathrm{Pr}_{17}(\cdot)$: Probability $\mathrm{Pr}_{17}(\cdot)$ in (13) is calculated by solving a Markov chain such that $\sum_{\mathcal{U}} \mathrm{Pr}_{17}(\cdot) = 1$ and $\mathrm{Pr}_{17}(\cdot) = \sum_{\mathcal{U}^{(t-1)}} \mathrm{Pr}_{17}(\cdot)\mathrm{Pr}_{16}(\cdot)$, where $\mathcal{U}$ is the set of all possible values of U_w and U_n, and $\mathcal{U}^{(t-1)}$ is the set of the same parameters at time $t-1$. Based on the assumption that the WPU has a higher priority of channel access than the NPU, the state transition probability $\mathrm{Pr}_{16}(\cdot)$ is derived as

$$\mathrm{Pr}_{16}(\cdot) \triangleq \mathrm{Pr}_{18}\left(U_w^{(t)} | U_w^{(t-1)}\right) \times \mathrm{Pr}_{19}\left(U_n^{(t)} | U_n^{(t-1)}, U_w^{(t)}, U_w^{(t-1)}\right), \quad (14)$$

where $\mathrm{Pr}_{18}(\cdot)$ denotes the probability of change in the number of WPUs U_w between time slots $t-1$ and t, and $\mathrm{Pr}_{19}(\cdot)$ denotes the probability of change in the number of NPUs U_n between time slots $t-1$ and t. We describe their derivation as follows.

k) Derivation of the probability of change in the number of WPUs and NPUs $\mathrm{Pr}_{18}(\cdot)$ and $\mathrm{Pr}_{19}(\cdot)$: Based on the introduced model, the interarrival and departure times follow the negative exponential distribution. Therefore, we can use equations for $G_x(i|U_x, \lambda_x)$ and $T_x(j|U_x, \mu_x)$, derived in (27) and (28) in Appendix A, respectively, in the similar way as in the derivation of (6) and (8). By denoting the available subchannels for NPU as $U_{e2} = \lfloor (M - U_w^{(t)} l_w)/l_n \rfloor$ at time t and $U_{e1} = \lfloor (M - U_w^{(t-1)} l_w)/l_n \rfloor$ at time $t-1$, we can derive $\mathrm{Pr}_{18}(\cdot)$ as

$$\mathrm{Pr}_{18}(\cdot) \triangleq \sum_{\{i,j\} \in \mathcal{K}_w} T_w\left(j | U_w^{(t-1)}, \mu_w\right) G_w\left(i | U_w^{(t)}, \lambda_w\right) \quad (15)$$

and $\mathrm{Pr}_{19}(\cdot)$ is given in (11) given at the bottom of the page, where $\mathcal{K}_w \triangleq \{i, j | i - j = U_w^{(t)} - U_w^{(t-1)}, j \leq U_w^{(t-1)}\}$, $\mathcal{K}_{n,a} \triangleq \{i, j | i - j = U_n^{(t)} - U_n^{(t-1)}, j \leq U_n^{(t-1)}\}$, and $K_{n,b} \triangleq \{i, j | U_n^{(t)} - U_n^{(t-1)} \leq i - j \leq U_{n,\max} - U_n^{(t-1)}, j \leq U_n^{(t-1)}\}$.

l) Derivation of the probability that M_e subchannels were detected as idle at time $t-1$, $\mathrm{Pr}_{10}(\cdot)$: Finally, $\mathrm{Pr}_{10}(\cdot)$ in (9) is calculated as

$$\begin{aligned}\mathrm{Pr}_{10}(\cdot) \triangleq & \sum_{\substack{\forall U_w^{(t-1)}, U_n^{(t-1)}, \\ S^{(t-1)}}} \mathrm{Pr}_{13}\left(M_a^{(t-1)} | U_w^{(t-1)}, U_n^{(t-1)}, S^{(t-1)}\right) \\ & \times \mathrm{Pr}_{15}\left(S^{(t-1)} | U_w^{(t-1)}, U_n^{(t-1)}\right) \\ & \times \mathrm{Pr}_{17}\left(U_w^{(t-1)}, U_n^{(t-1)}\right). \end{aligned} \quad (16)$$

2) Derivation of Sensing Overhead $\eta(\cdot)$: The value of $\eta(\cdot)$ depends on the sensing stage, because a longer sensing time for one stage can reduce $\eta(\cdot)$, whereas a shorter sensing time for another stage can increase $\eta(\cdot)$. We recall the variable S, introduced in Appendices B and C, which indicates the sensing stage such that $S = 0$ denotes the case when the OSA network performs only coarse sensing without switching to fine sensing, and $S > 0$ denotes the case when the OSA network performs

$$\mathrm{Pr}_{19}(\cdot) \triangleq \begin{cases} \sum_{\{i,j\} \in \mathcal{K}_{n,a}} T_n\left(j | U_n^{(t)}, \mu_n\right) G_n\left(i | U_n^{(t-1)}, \lambda_n\right), & U_n^{(t-1)} \leq U_{e1}, U_n^{(t)} < U_{e2}, \\ \sum_{\{i,j\} \in \mathcal{K}_{n,b}} T_n\left(j | U_n^{(t)}, \mu_n\right) G_n\left(i | U_n^{(t-1)} + i - j, \lambda_n\right), & U_n^{(t-1)} \leq U_{e1}, U_n^{(t)} = U_{e2}. \end{cases} \quad (11)$$

coarse sensing and immediately switches to fine sensing. In particular, $S=1$ denotes the case when the OSA network detects the idle subchannel and $S=2$ denotes the case that no idle subchannel is detected so that the network waits until the next sensing period without transmitting data.

Defining $\mathrm{Pr}_0(S, M_e)$ as the joint probability that the current sensing stage is equal to S and the number of subchannels detected as idle is M_e, we can calculate η as

$$\eta(M_e) \triangleq \mathrm{Pr}_0(0, M_e)\frac{t_f-\tau_a}{t_f} + \mathrm{Pr}_0(1, M_e)\frac{t_f-\tau_a+\tau_f}{t_f}. \quad (17)$$

Note that there is no $\mathrm{Pr}_0(2, M_e)$ in (17), because for $S=2$, no data can be transmitted; therefore, the ratio of the data transmission time to the total frame length is zero. Finally, we can derive $\mathrm{Pr}_0(\cdot)$ in (17) as (16) by removing $S^{(t-1)}$ from the lowest bound of summation.

B. Case $S_0N_0B_1$: General Sensing, Channel Blocking, and Channel Bonding

There are two major changes for the analysis of the $S_0N_0B_1$ case compared to $S_0N_1B_1$. First, the number of subchannels detected as idle should be the integer multiples of Y, because in this case, the smallest quantity of idle bandwidth is one channel. Second, the number of available subchannels is determined not only by the number of the NPUs but by the position of the NPUs in the spectrum as well. For example, if two NPUs appear on different subchannels in the same channel, the SU cannot utilize that channel. If NPUs occupy subchannels located in two different channels, these two channels cannot be used by SUs. Considering these changes, we need to modify probabilities related to the number of subchannels detected as idle and the sensing stage used, i.e., $\mathrm{Pr}_{11}(\cdot)$ in (12), $\mathrm{Pr}_{13}(\cdot)$ in (31), and $\mathrm{Pr}_{15}(\cdot)$ in (33). Note that the other probabilities remain the same, as derived in Section IV-A. In the modification of the aforementioned expressions, we assume $\delta_f \approxeq \delta_a \approxeq 1$ to reduce the complexity of calculations. In general, the OS-OFDMA system needs to keep a high detection probability to protect the PUs, which makes this approximation reasonable. Note, however, that we will still consider the effect of false alarms. Thus, even if there is no PU on the spectrum, the SU may falsely detect an idle subchannel as busy. Moreover, without loss of generality, we assume that a WPU occupies one channel, i.e., $l_w = Y$.

To modify $\mathrm{Pr}_{11}(\cdot)$ based on (12), we observe that the change of the number of PUs between times t and $t-1$ may affect the change of the position of the PUs and, as a result, can make an impact on the number of channels detected as idle at time t. Thus, introducing the conditional probability of the number of idle subchannels as $\mathrm{Pr}_{23}(M_a^{(t)}|U_w^{(t)}, U_n^{(t)}, S^{(t)}, M_a^{(t-1)}, U_w^{(t-1)}, U_n^{(t-1)}, S^{(t-1)})$, $\mathrm{Pr}_{11}(\cdot)$ in (12) is newly defined as

$$\begin{aligned}\mathrm{Pr}_{11}(\cdot) \triangleq\ & \mathrm{Pr}_{13}\left(M_a^{(t-1)}|U_w^{(t-1)}, U_n^{(t-1)}, S^{(t-1)}\right)\\ &\times \mathrm{Pr}_{23}\left(M_a^t|M_a^{(t-1)}, U_w^{(t)}, U_w^{(t-1)},\right.\\ &\left.\qquad U_n^{(t)}, U_n^{(t-1)}, S^{(t)}, S^{(t-1)}\right), \quad (18)\end{aligned}$$

where $\mathrm{Pr}_{23}(\cdot)$ is derived in Appendix E. Finally, $\mathrm{Pr}_{13}(\cdot)$ and $\mathrm{Pr}_{15}(\cdot)$ are modified in Appendices D and F, respectively.

C. Case $S_0N_0B_0$: General Sensing, Channel Blocking, and Fixed Channel Selection

The analysis in this section is based on the derivation based on Section IV-B, because this option still considers subchannel non-notching. The major change here is that we perform analysis for data transmission on one channel instead of all X channels. This change affects the valid condition for $\mathrm{Pr}_7(\cdot)$ in (6) and l_v in (7). Because the maximum number of available subchannels is limited to Y, $U_e^{(t)}$ and $U_e^{(t-1)}$ become $\lfloor \min(Y/l_n, M_e^{(t)}/l_n)\rfloor$ and $\lfloor \min(Y/l_n, M_e^{(t-1)}/l_n)\rfloor$, respectively. Moreover, considering that the maximum number of channels that are utilized by VBR is also limited to one channel, then (7) should be modified as

$$l_v = \begin{cases} \frac{\min\left(Y, M_a^{(t-1)}\right) - U_c^{(t-1)}}{U_v^{(t-1)}}, & U_v^{(t-1)} > 0,\\ 0, & U_v^{(t-1)} = 0.\end{cases} \quad (19)$$

In addition, we need to modify $\mathrm{Pr}_6(\cdot)$ in (9), i.e., the probability of change of the subchannel count detected as idle, considering the limitations of the available subchannels. Even if a SU detects more than one idle channel, the SU will utilize only one channel. In terms of the definition, we have to sum all probabilities that the number of subchannels detected as idle is greater than or equal to Y to calculate the probability that one channel, i.e., Y subchannels, are detected as idle. Thus

$$\mathrm{Pr}_6(\cdot) \triangleq \begin{cases} \frac{\mathrm{Pr}_9(0,0)}{\mathrm{Pr}_{10}(0)}, & M_a^{(t)} = 0,\ M_a^{(t-1)} = 0,\\ \frac{\sum_{x=Y}^{M} \mathrm{Pr}_9(0,x)}{\sum_{x=Y}^{M} \mathrm{Pr}_{10}(x)}, & M_a^{(t)} = 0,\ M_a^{(t-1)} > 0,\\ \frac{\sum_{x=Y}^{M} \mathrm{Pr}_9(x,0)}{\mathrm{Pr}_{10}(0)}, & M_a^{(t)} > 0,\ M_a^{(t-1)} = 0,\\ \frac{\sum_{x,y\in\{Y,\ldots,M\}} \mathrm{Pr}_9(x,y)}{\sum_{x=Y}^{M} \mathrm{Pr}_{10}(x)}, & M_a^{(t)} > 0,\ M_a^{(t-1)} > 0.\end{cases} \quad (20)$$

D. Case $S_1N_0B_0$: Active Channel Sensing, Channel Blocking, and Fixed Channel Selection

In this case, the SU performs coarse sensing for only one channel that is currently utilized for data transmission. Thus, the PU on a channel that is not used by the SU does not affect the OSA network, and as a result, the sensing stage of the OSA network becomes more sensitive to the location of the PUs in the radio spectrum. Therefore, probabilities that are related to the sensing stage S, such as $\mathrm{Pr}_{12}(\cdot)$ in (13), $\mathrm{Pr}_{15}(\cdot)$ in (33), and $\mathrm{Pr}_{20}(\cdot)$ in (32), need to be updated. Due to space constraints, we refer to [49, Sec. III-D] for the details of the derivation.

E. Derivation of the Connection Blocking Rate for the CBR Traffic

Due to the assumption that the CBR traffic cannot be buffered once all channels are occupied by the PU (see Section III-A2), we define the CBR connection blocking rate as the average number of CBR connections that are blocked by the PU appearance per second.[8] We consider the $S_0N_1B_1$ case, because the blocking probabilities for the other three design cases are accordingly calculated as in (21), shown at the bottom of the page.

By denoting $\Pr_B(k)$ as the probability that k CBR connections are blocked in a frame, we can calculate the CBR connection blocking rate as

$$R_B = \sum_{k=0}^{U_{c,\max}} k \Pr_B(k)/t_f. \quad (22)$$

Because the number of blocked connections k depends on how many CBR users are in the system and how many subchannels are available, we decompose $\Pr_B(k)$ in (22) as

$$\Pr_B(k) \triangleq \sum_{\mathcal{W}} \Pr_b\left(k|U_c^{(t)}, U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)}\right) \times \Pr_c\left(U_c^{(t)}, U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)}\right), \quad (23)$$

where $\mathcal{W}$ is the set of all possible values of $U_c^{(t)}$, $U_c^{(t-1)}$, $M_a^{(t)}$, and $M_a^{(t-1)}$. $\Pr_c(\cdot)$ can be calculated by summing up $\Pr_4(\cdot)\Pr_3(\cdot)$ for all possible values of $U_v^{(t-1)}$ and $U_v^{(t)}$.

In (22), $\Pr_B(0)$ does not affect R_B the calculation, because it is multiplied by $k=0$; thus, we focus on the case $k>0$. We define $\Pr_{b+}(k|U_c^{(t)}, U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)})$ as $\Pr_b(k|U_c^{(t)}, U_c^{(t-1)}, M_a^{(t)}, M_a^{(t-1)})$ for $k>0$. Recall that $U_a^{(t)} = \lfloor M_a^{(t)}/l_c \rfloor$ and $U_a^{(t-1)} = \lfloor M_a^{(t-1)}/l_c \rfloor$. For supporting variables i and j, denoting that i connections are newly generated and j connections are released, the instant number of CBR connections before spectrum sensing is $U_c^{(t-1)} + i - j$, and the number of actual CBR connections after spectrum sensing is $U_c^{(t)}$. Thus, $i - j = k + U_c^{(t)} - U_c^{(t-1)}$. Therefore, by defining $\mathcal{K}_b(k) \triangleq \{i,j|i-j=k+U_c^{(t)} - U_c^{(t-1)}, j \le U_c^{(t-1)}\}$, we have $\Pr_{b+}(\cdot)$, as given in (21) given at the bottom of the page.

F. Application of the Proposed Analytical Model: Example

One of the main application domains of the proposed model is to optimize the performance of the network operation, given constraints that network operators have to deal with. Here, we give an example of such an optimization framework.

Usually, the operators want to maximize the total network throughput while, at the same time, not violating the minimum throughput requirements of each QoS class. Thus, for example, for each system design scenario $S_xN_yB_z$, we can construct the following optimization problem:

$$\max H \quad (24a)$$

$$\text{s. t. } \delta_a \le \delta_{a,r}, \phi_a \le \phi_{a,r}, H_c \le H_{c,r}, H_v \le H_{v,r} \quad (24b)$$

$$\text{given } U_{c,\max}, U_{v,\max}, L, X, C, Y, t_f, 1/\lambda_x, 1/\mu_x, \tau_a, \tau_f \quad (24c)$$

where $x = \{c, v\}$, and $\delta_{a,r}$, $\phi_{a,r}$, $H_{c,r}$ and $H_{v,r}$ are the minimum required probability of detection, minimum required probability of false alarm, minimum required throughput of CBR connection, and minimum required throughput of VBR connection, respectively. Once the total system throughput H has been calculated for each design option, the operator should select the option that obtains the highest H.

V. Numerical Results

In this section, we provide performance results for all considered options. Due to space constrains, we focus only on throughput metric H, because the numerical results on blocking probability P_B were already provided in [1]. We note that all analytical results were verified through simulations using a method of batch means for a 90% confidence interval. Each simulation run, with a warm-up period of 10 000 network events, was divided into 100 batches, where each batch contained 10 000 network events. The custom simulation package used in this paper was written in MATLAB. We also note that, on a computer with MATLAB R2010a and a Mac OS X 10.7.1 operating system installed on a Mac Book Pro with 2-GHz Intel Core i7 and 4-GB 1333-MHz DDR3 memory, the computation of throughput for one set of parameters takes approximately less than 60 s.

Due to many parameters considered, we limit our numerical investigation to the four most representative case studies. That is, we consider the impact of varying number of NPUs, the impact of varying PU activity, the impact on two-stage spectrum sensing design, the impact of adjacent channel interference, and the impact of cochannel interference on the system throughput. Results are presented in Sections V-B–E, respectively. Furthermore, we investigate the delay performance of the considered OS-OFDMA system through NS-2 simulations in Section V-F.

A. Calculation of the Average Subchannel Capacity C

Before we proceed with the presentation, we need to comment on the calculation of C. Following the IEEE 802.22 model [5], we separately consider the PHY capacity C_p and

[8]We note that, in this paper, we consider the forced termination probability and the blocking probability as one metric, because in our metric, blocking can happen due to insufficient radio resources or due to the arrival of (any type of) PU.

$$\Pr_{b+}(\cdot) \triangleq \begin{cases} \sum_{\{i,j\}\in\mathcal{K}_b(k)} T_c\left(j|U_c^{(t)}, \mu_c\right) G_c\left(i|U_c^{(t-1)} + i - j, \lambda_c\right), & U_c^{(t-1)} \le U_a^{(t-1)}, U_c^{(t)} = U_a^{(t)}, \\ 0, & \text{otherwise} \end{cases} \quad (21)$$

the MAC-layer overhead ξ such that $C = (1 - \xi)C_p$, where $C_p = 460.8$ kb/s.[9]

For the MAC-layer overhead ξ, we consider the frame structure of the IEEE 802.22 such that one downlink OFDM symbol of all subchannels is assigned to a preamble and two downlink OFDMA symbols of all subchannels are assigned to management messages. In addition, considering errors on the subchannels, we assume a bit error rate of 10^{-6}. Hence, we calculate the MAC-layer overhead reduction factor as $1 - \xi = 13/16 \times (1-10^{-6}) = 0.8125$. Therefore, the total subchannel capacity is $C = 374.4$ kb/s.

B. Impact of Varying Number of NPUs on the OS-OFDMA Design

Throughout this section, we assume that $X = 4$ channels are available and split into $Y = 10$ subchannels of bandwidth $b = 492$ kHz. The frame length is set to $t_f = 20$ ms, which represents the length of two frames of the IEEE 802.22 [5], i.e., it represents the time that the SU device searches for OFDM preambles on a given channel and highly conservative value of an interframe sensing interval [5, Tab. 233]. The detection and false-alarm probability for the coarse sensing case are $\delta_a = 0.99$ and $\phi_a = 0.1$, respectively, whereas for the fine sensing case, $\delta_a = 1$ and $\phi_a = 0$, respectively. The sensing time during coarse sensing is $\tau_a = 0$. Because we have assumed that uplink and downlink are divided by time-division duplex and coarse sensing is performed in the uplink, as shown in [5], the sensing overhead is zero. In the fine-sensing phase, $\tau_f = (3/5)t_f$, modeling three consecutive frames that are used for the fine sensing and the following two frames that are used for data transmission until the next sensing period. Furthermore, we assume that $l_c = 1$, $l_w = 10$, and $l_n = 1$ subchannels are allocated to CBR, NPU, and WPU connections, respectively. Note that the number of subchannels that are assigned to VBR connections l_v varies, depending on the network state. The maximum number of users of each class is $U_{v,\max} = 2$, $U_{c,\max} = 10$, and $U_{w,\max} = 2$, investigating the impact of NPUs, and $U_{v,\max} = 2$, $U_{c,\max} = 10$, and $U_{n,\max} = 10$, investigating impact of WPUs. These values correspond to a small network and allow for an easier understanding of the subsequent numerical results.

In addition, for the purpose of this section, we set up the interarrival and departure times by taking into account the IEEE 802.22 network, where many active licensed users operate over the TV band. Because, in general, the traffic pattern of PUs for such a case is not well known (more discussion on this aspect is presented in Section V-C), for the WPU, we keep the wireless assist video devices [50] in mind, which can be assumed to broadcast, on the average, 4 h of signal transmission for every 12 h, on the average, in this scenario. For the NPU, we consider an environment with numerous WMs and assume that they appear every 2 h, on the average, and utilize channels for 1 h on the average. For CBR, considering voice or video transmission, we assume that, on the average, a 5 min long CBR connection is generated for every 5 min on the average. For VBR, we assume that data traffic is generated every 2 h on the average and continues for 2 h if one channel is assigned for a VBR connection. For simulation efficiency, because we operate in large parameter ranges, we scale them down by setting the CBR connection arrival rate to 1 s by preserving the ratios between all traffic parameters, i.e., we normalize the average interarrival and departure times of all users in the unit of 5 min by dividing them by 300 s. Thus, for a large number of users, the interarrival time becomes shorter. For the analysis, we calculate the interarrival time by dividing the individual interarrival time by the maximum number of users. In summary, $1/\lambda_w = 144/U_{w,\max}$ s, $1/\lambda_n = 24/U_{n,\max}$ s, $1/\lambda_c = 1/U_{c,\max}$ s, $1/\lambda_v = 12/U_{v,\max}$ s, $1/\mu_w = 48$ s, $1/\mu_n = 12$ s, $1/\mu_c = 1$ s, and $1/\mu_v = 240$ s.

The results are presented in Fig. 1. The throughput of every OS-OFDMA design option decreases with increasing numbers of NPUs and WPUs. First, we observe that $S_0N_1B_1$ is the best design option when the total and VBR throughput is concerned, which is due to the highest flexibility in exploiting all spectrum opportunities. Second, interestingly, with a low number of NPUs and WPUs, the CBR throughput is higher for $S_1N_0B_0$ than for $S_0N_1B_1$, whereas with the high number of NPUs and WPUs, the opposite holds; see Fig. 1(b) and (e). This case is because of the sensing overhead of the fine sensing that is more frequently performed for $S_0N_1B_1$ than for $S_1N_0B_0$. Third, there is no difference in the CBR throughput between $S_0N_0B_1$ and $S_0N_0B_0$ when the number of NPUs varies. This case is because, in this network setup, the CBR, which has higher priority than the VBR, utilizes enough resources, although channel bonding is not applied. Fourth, the $S_0N_0B_1$ design option is extremely sensitive to the activity of the NPUs. The throughput of this design option rapidly decreases as the number of NPUs increases; compare Fig. 1(a) with Fig. 1(c). This effect is not visible, however, when the number of NPUs is kept fixed but the number of WPUs changes; see Fig. 1(d) and (f) and compare with Fig. 1(a) and (c), respectively. This case is because $S_0N_0B_1$ is sensitive to the position of NPUs in the spectrum, i.e., the lack of subchannel notching (N_0) causes this option to perform worse.

Furthermore, we demonstrate a benefit of the active channel sensing strategy in two-stage sensing. Surprisingly, the total throughput of $S_1N_0B_0$ is greater than the total throughput of $S_0N_0B_1$ for large number of NPUs and WPUs [see Fig. 1(a) and (d)], although the implementation for $S_0N_0B_1$ enables wider bandwidth sensing than $S_1N_0B_0$. This is because, for $S_0N_0B_1$, due to channel bonding, the probability that the OSA network needs to sense the channel is much higher, and the network needs to perform sensing often, whereas for $S_1N_0B_0$, only the actively used channel is sensed.

Note that the simulation results agree with the analysis in all figures. A slight mismatch between simulation and analysis for cases $S_0N_0B_1$, $S_0N_0B_0$, and $S_1N_0B_0$ in Fig. 1(e) is a result of the approximation that was used in calculating the throughput for these design options; see (38). More discussion on this issue is presented in Section V-C.

[9]Assumptions: 16-ary quadrature-amplitude modulation (16-QAM) with 4 b per OFDM symbol and 1/2 channel coding per subcarrier; for a guard band for NPUs, six subchannels of the IEEE 802.22 represent one subchannel in the system model. Uplink and downlink are time-division duplexed, where 16 and eight symbols are assigned to the downlink and uplink, respectively.

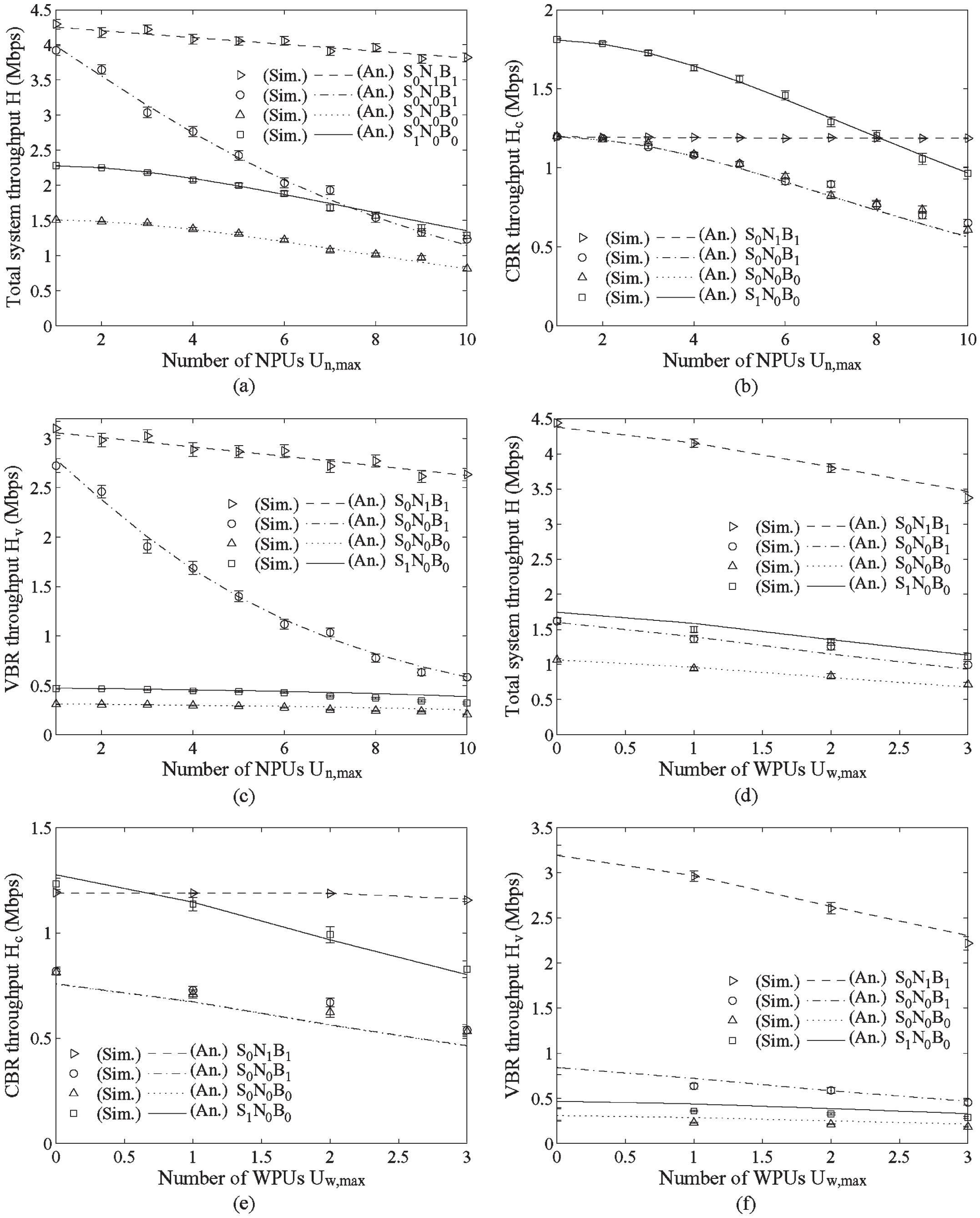


Fig. 1. Performance of different OS-OFDMA options as a function of (a)–(c) NPU and (d)–(f) WPU for $X = 4$, $Y = 10$, $M = 40$, $t_f = 20$ ms, $\delta_a = 0.99$, $\phi_a = 0.1$, $\tau_a = 0$, $\delta_f = 1$, $\phi_f = 0$, $\tau_f = (3/5)t_f$, $C = 374.4$ kbps, $U_{w,\max} = 2$ (WPU), $U_{n,\max} = 10$ (NPU), $l_w = 10$, $l_n = 1$, $U_{c,\max} = 10$, $l_c = 1$, and $U_{v,\max} = 2$. (a) and (d) Total system throughput. (b) and (e) Throughput of CBR connections. (c) and (f) Throughput of VBR connections.

C. Impact of PU Activity on the OS-OFDMA Design

To investigate the impact of varying PU activity on the performance of different OS-OFDMA designs, for ease of explanation, we have considered focusing only on NPUs. Then, as a case study, we consider WMs as an example of NPU. The parameters of the OS-OFDMA are the same as in Section V-B. Before presenting the performance results, we need to estimate the most realistic values of WM activity descriptors, i.e., average arrival rate and channel occupancy time.

From the perspective of this paper, WMs can be categorized into the following two main groups: 1) static in the coverage area of the OS-OFDMA BS, such as WMs in meetings or conference rooms, and 2) mobile in the coverage area of OS-OFDMA BS, such as WMs that belong to broadcasters (e.g., radio and TV), sports-related entities (e.g., communication between referees or between team members and coaches), or special-event groups (e.g., microphone usage during merchandizing or protests). For ease of understanding, we focus here on mobile WMs, noting that, due to the random activity pattern of WMs, static WMs can also be approximated as moving into the coverage area of the OS-OFDMA BS.

In the case of average NPU channel occupancy time, we set it to a value between 1 and 4 h, believing that this represents a common activity time. More discussion is needed, however,

TABLE II
SCENARIOS FOR THE ANALYSIS OF NPU ACTIVITY IMPACT ON THE PERFORMANCE OF OS-OFDMA DESIGNS

Nickname	"heavy urban"	"light urban"	"event"
Location in US	Los Angeles, CA	Madison, WI	Staples Center
Users/mi^2, ρ	4708.2	2701.0	7452.7
Activity, $1/\mu_n$ h	1	1	4
$U_{n,\max}$	8	3	18

on the arrival rate of the WMs. Because the potential number of WMs is location dependent, we have set up three different network scenarios, representing different places in the U.S. (see Table II), which differ in population density ρ and activity time $1/\mu_n$. We assume that the OS-OFDMA BS covers a fraction of the area of diameter $L = 2$ mi (for all scenarios) of the considered location, whereas the WMs move in and out of the BS circular coverage with a certain speed $v = 1.5$ mi/h (for all scenarios). Then, using a fluid flow model approximation [51], we calculate the average crossing rate of the WMs to that area and directly translate it to an average arrival rate of WMs on any of the subchannels. That is, $\lambda_n = \rho h \pi L v$, where $1/h$ denotes number of inhabitants per one active WM in the considered location. Because the value of h is not reliably known,[10] we assume that one WM is present per 300 inhabitants (for all scenarios), and such a WM is active for 10% of the time. Finally, $U_{n,\max} = \max(\lfloor \pi (L/2)^2 \rho h \rfloor, 1)$ in this case. We set the interarrival and departure times for other users as the same value as in Section V-B. In addition, for analysis, we normalize all time parameters in the unit of 5 min, as shown in Section V-B.

The results are separately grouped for the total average network throughput, CBR throughput, and VBR throughput; see Figs. 2–4, respectively. We have chosen to vary the number of CBR connections in all figures as a parameter, because in our model, the CBR connection is the most QoS-sensitive and capacity-demanding SU traffic class. First, we immediately observe that $S_0N_1B_1$ implementation obtains the highest throughput averaged over all scenarios. The larger the activity of the WMs, the bigger the difference between $S_0N_1B_1$ and the remaining implementations; for example, compare Fig. 2(b) and (c). Option $S_0N_1B_1$ obtains a throughput around 3 Mb/s, even in the "event" scenario. This is due to the maximum utilization of the remaining channel capacity by subchannel notching and channel bonding. As the NPU activity increases all implementations reach almost-zero throughput, whereas $S_0N_1B_1$ still obtains reasonable performance. The worst performance is obtained for $S_0N_0B_0$, whereas $S_1N_0B_0$ and $S_0N_0B_1$ are in between the extreme cases.

As the activity of the WMs decreases, i.e., it changes from an "event" scenario to a "light urban" scenario, the difference between the obtained throughput for $S_0N_1B_1$ and the remaining implementation becomes smaller; for example, compare Fig. 3(a) with Fig. 3(b). Interestingly, the individual relation between the implementations stays the same for each scenario, whereas at lower WM activities, the $S_1N_0B_0$ implementation becomes better than $S_0N_1B_1$ for the CBR throughput; compare Fig. 3(a) with Fig. 3(b). This case is for the following two reasons: 1) As the activity of the WMs becomes smaller, so does the fragmentation of the available bandwidth, and the CBR has more options for the selection of required channels; and 2) because there is no bonding of channels and the OS-OFDMA network senses only active channels due to the active channel sensing strategy, the OS-OFDMA network does not have to frequently switch to fine sensing, and the saved time for sensing can be used for active data transmission. The worst situation, in terms of network scenario, is the "event" scenario. Due to the long channel dwell time by the NPU, i.e., 4 h, the throughput for all implementations, except for $S_0N_1B_1$, reaches zero. We also conclude that, in scenarios where the activity of the WMs is low, such as in the "light urban" scenario, the users of systems based on OS-OFDMA are promised to obtain high QoS [see Figs. 2(b)–4(b)], irrespective of the implementation.

A separate comment is needed for the simulation verification of the results. In all cases, the $S_0N_1B_1$ implementation perfectly matches the simulations, irrespective of the parameters selected. However, due to the approximations assumed for the remaining OS-OFDMA implementations [see again (39)], the slight discrepancy is particularly visible for the scenarios with a high NPU activity rate; for example compare Fig. 3(a) with Fig. 3(b). The results prove, on the other hand, that the developed model works very well for low PU activities, which is the typical case in real-life PU occupancy statistics [34]. Still, for each case study, the relation between each OS-OFDMA implementation is well captured for any value of the parameters considered, whereas for the majority of the cases, the mismatch between simulations and analysis is less than 10%.

D. Impact of Two-Stage Spectrum Sensing Options on the OS-OFDMA Design

The next experiment considers the effect of sensing design parameters on the performance of OS-OFDMA designs. For this investigation, we change the sensing time of coarse sensing, which has a direct effect on the false-alarm probability and makes a significant impact on the frequency of switching to fine sensing (and, as a result, on the throughput of the system). We keep other parameters the same as in the first experiment described in Section V-B, except for $U_{n,\max} = 2$, to see the effect of coarse sensing clearer, and $U_{c,\max} = 10$. We do not alter parameters of the fine-sensing phase, because we want to explore the benefit of two-stage sensing, and the coarse sensing phase is a common element of every sensing method, including single-stage sensing.

Considering a Rayleigh channel with additive white Gaussian noise, we calculate the false-alarm probability p_{10} and detection probability p_{11} for an individual SU user as shown in [20, eq. (3)] and [20, eq. (4)], respectively. The level of the PU signal received at each SU detector is assumed as $\gamma = -10$ dB, considering perfect channel orthogonality and no interference

[10] The only credible report that we were able to find was [52]. The estimation using data present in this report was based on a simple calculation. According to [52, Sec. A2], there were 1 924 431 wireless microphone shipments in the European Union (EU) between 2002 and 2006, which translates to ≈1 wireless microphone per 1000 EU inhabitants (assuming a constant level of wireless microphone shipments per year). Note that the value of 35 000–70 000 licensed wireless microphone operations in the U.S. presented in [53] was not substantiated with any reference.

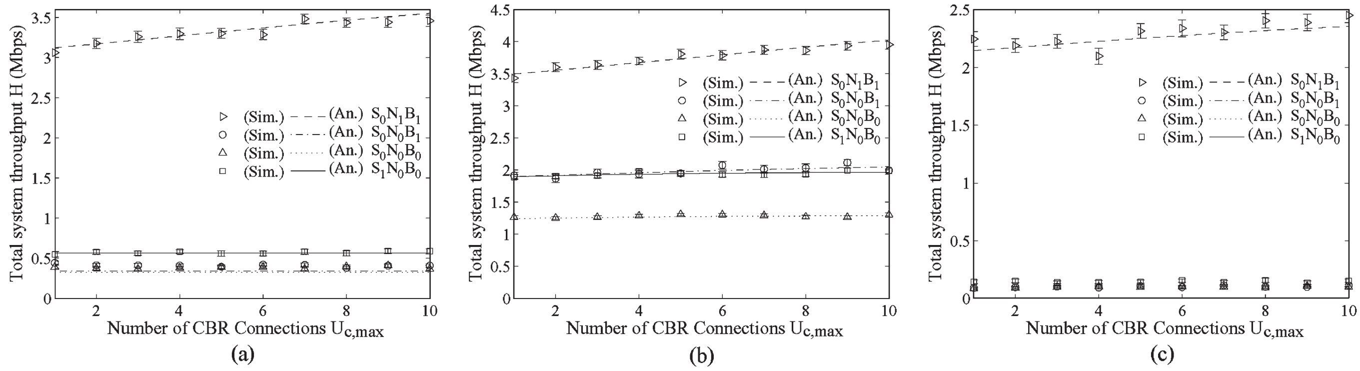


Fig. 2. Total throughput of different OS-OFDMA implementations for all network cases. The parameter setup and the ordering of the figures is the same as in Fig. 1. (a) Heavy urban. (b) Light urban. (c) Event.

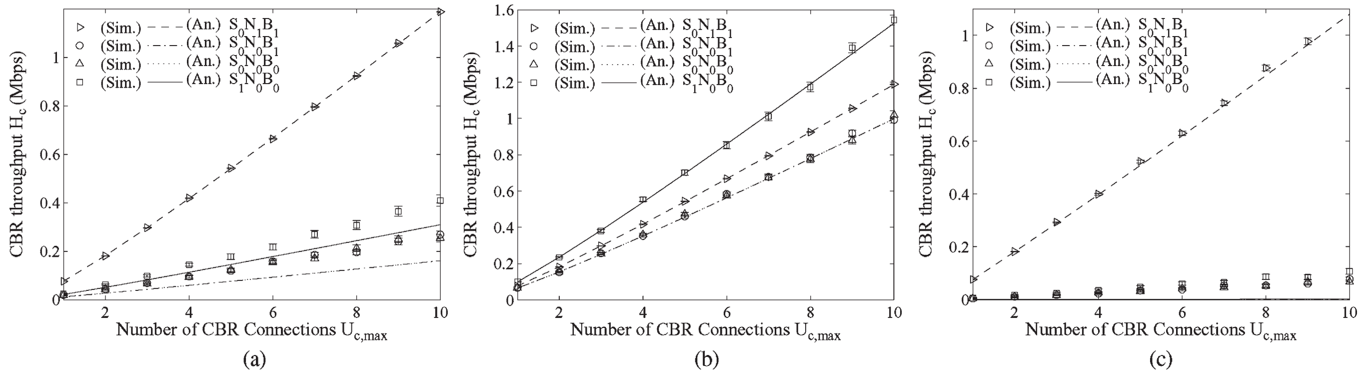


Fig. 3. CBR throughput of different OS-OFDMA implementations for all network cases. The parameter setup and the ordering of the figures is the same as in Fig. 1. (a) Heavy urban. (b) Light urban. (c) Event.

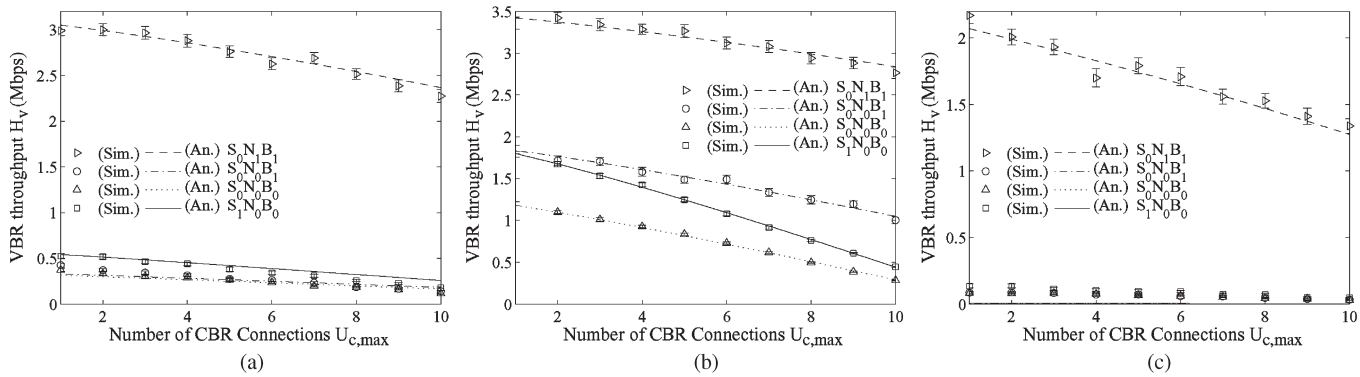


Fig. 4. VBR throughput of different OS-OFDMA implementations for all network cases. The parameter setup and the ordering of the figures is the same as in Fig. 1. (a) Heavy urban. (b) Light urban. (c) Event.

from adjacent channels (this assumption will be relaxed and investigated in more detail in Section V-E). Then, according to [20, Sec. III-B], we can derive p_{11} as a function of p_{10} and τ_a for given average PU signal-to-noise ratio (SNR) and subchannel bandwidth b by adapting the detection threshold θ. Assuming cooperative sensing of all CBR and VBR users and OR logic for a combining scheme, we calculate the system false-alarm probability as

$$\phi_a = 1 - (1 - p_{10})^{(U_{c,\max}+U_{v,\max})} \tag{25}$$

and the system detection probability δ_a as (25), replacing p_{10} with p_{11}. Note that, in this paper, the number of cooperating users in (25) can arbitrarily be set as a fraction of $U_{c,\max} + U_{v,\max}$, depending on the cooperative sensing scheme or sensing order. In addition, the fusion rule can arbitrarily be set in this paper, depending on the choice of cooperation algorithm. In addition, note that, if we assume that each node of the OS-OFDMA network is located at different physical locations, we can adapt (25) such that

$$\phi_a = 1 - \prod_{i \in \mathcal{U}_m} 1 - p_{10}^{(i)}, \tag{26}$$

where $\mathcal{U}_m$ is the total set of users that utilize CBR and VBR connections and participate in the cooperation process, whereas $p_{10}^{(i)}$ is the individual probability of false alarm for a user at a particular location i. Probability $p_{10}^{(i)}$ can be calculated in the

TABLE III
SENSING TIME AND THE RESPECTIVE FALSE-ALARM PROBABILITY FOR THE EXPERIMENTS INTRODUCED IN SECTIONS IV-D AND V-E

τ_a (ms)	0	0.5	1	1.5	2	2.5	3	3.5	4
ϕ_a ($\gamma = -8$ dB)	1	0.0227	0.0004	1.08e-05	2.57e-07	6.30e-09	1.56e-10	3.95e-12	1.01e-13
ϕ_a ($\gamma = -10$ dB)	1	0.2308	0.0446	0.0087	0.0018	0.0004	0.0001	1.57e-4	0.333e-4
ϕ_a ($\gamma = -12$ dB)	1	0.5857	0.3090	0.1585	0.0808	0.0413	0.0211	0.0109	0.0056

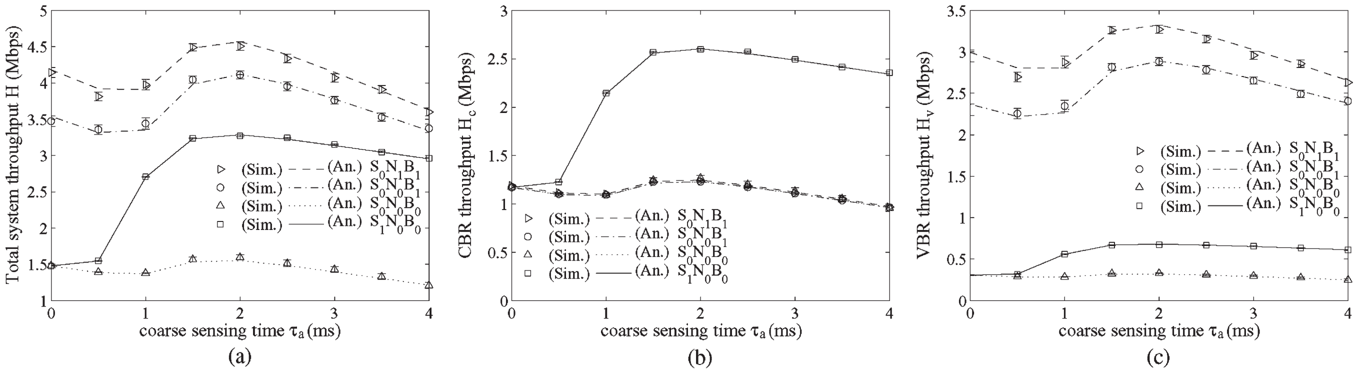


Fig. 5. Throughput of OS-OFDMA implementations, (a) total, (b) CBR, and (c) VBR, as a function of coarse sensing time. The parameter setup is the same as in Fig. 1, except for $U_{n\,\max} = 2$, $U_{c,\max} = 10$, whereas τ_a and ϕ_a are given in Table III.

same way as in [20, eq. (4)], assuming $\gamma = \gamma(i)$, where $\gamma(i)$ is the signal level from the PU received by the SU at location i.

In this evaluation, we keep the detection probability $\delta_a = 0.99$ and change the sensing time for the coarse sensing such that $\tau_a = (0, 4)$ ms. Note that $\tau_a = 0$ ms represents single-stage sensing. Table III presents the calculated false-alarm probability ϕ_a based on the assumed sensing time τ_a.

The results are presented in Fig. 5. The first interesting observation is that two-stage sensing does not always provide better performance than single-stage sensing. Comparing the total throughput at $\tau_a = 0$ with $\tau_a \approxeq (0.5, 1)$ ms of all OS-OFDMA options, two-stage sensing shows worse performance than single-stage sensing. This result is due to the high probability of false alarm for this range of τ_a; see Table III. In addition, for this network setup, the throughput is maximized at $\tau_a = 2$ ms and is larger than for $\tau_a = 0$, which confirms that two-stage sensing can, indeed, benefit all OS-OFDMA operations. This result also confirms that the design choice of the IEEE 802.22 for the spectrum sensing method was correct. When τ_a increases beyond the point for which the throughput is the largest, the throughput of all OS-OFDMA implementations starts to rapidly decrease. This case is because the sensing overhead starts to dominate over potential improvement from the decreased false-alarm rate. This so-called sensing-throughput tradeoff is in agreement with a similar investigation in the context of OSA ad hoc networks [20]. Note that the relation between sensing time and the obtained throughput are the same when looking at the total, CBR, and VBR throughput; see the shapes of all curves in Fig. 5(a)–(c). In addition, the different orders in the obtained throughput for each OS-OFDMA implementation are due to the specific OS-OFDMA options and not due to the spectrum sensing parameters selected. For this case, for example, compare the position of $S_1N_0B_0$ in Fig. 5(a) with the position of the same implementation in Fig. 5(b). For more details on this aspect, refer to Section V-C. Finally, note that the simulation results match well with the analysis for all OS-OFDMA implementations.

Referring to Section IV-F, where we have presented a throughput optimization framework, we can apply the same idea to maximize the throughput from the perspective of two-stage spectrum sensing. In this case, in optimization (24), we need to change the constraints in (24b) by adding $\tau_f \geq \tau_{f,r}$ and $\tau_a \geq \tau_{a,r}$, where $\tau_{a,r}$ and $\tau_{f,r}$ are the minimum required coarse- and fine-sensing times, respectively, while completely removing τ_a and τ_f from (24c).

E. Impact of Adjacent Channel Interference on the OS-OFDMA Design

In this section, we investigate the impact of adjacent channel interference on the OS-OFDMA design throughput from the perspective of two-stage sensing, complementing the results obtained in Section V-D. We consider the same parameter setup as in Section V-D. The results are presented in Fig. 6 for CBR, VBR, and total traffic.

So far, we have assumed that, in any OS-OFDMA implementation, the only source of received PU signal corruption is through environmental noise and propagation effects. Furthermore, we have assumed that two or more collocated SUs in one spectrum band would not cause any interference to other services, nor would the performance of the PU spectrum sensing process be degraded by cochannel or adjacent channel interference. Here, we relax this assumption and particularly focus on the effect of adjacent channel interference on the overall OS-OFDMA performance through the perspective of the PU spectrum sensor.[11] The reason for interference to the PU detector may be due to subcarrier leakage and/or imperfect filtering at the OFDM PHY layer.

[11] Another investigation of OFDMA interference from the spectrum sensing perspective can be found, for example, in [54]. Cochannel interference in the context of OFDMA with spectrum pooling has been analyzed, for example, in [55].

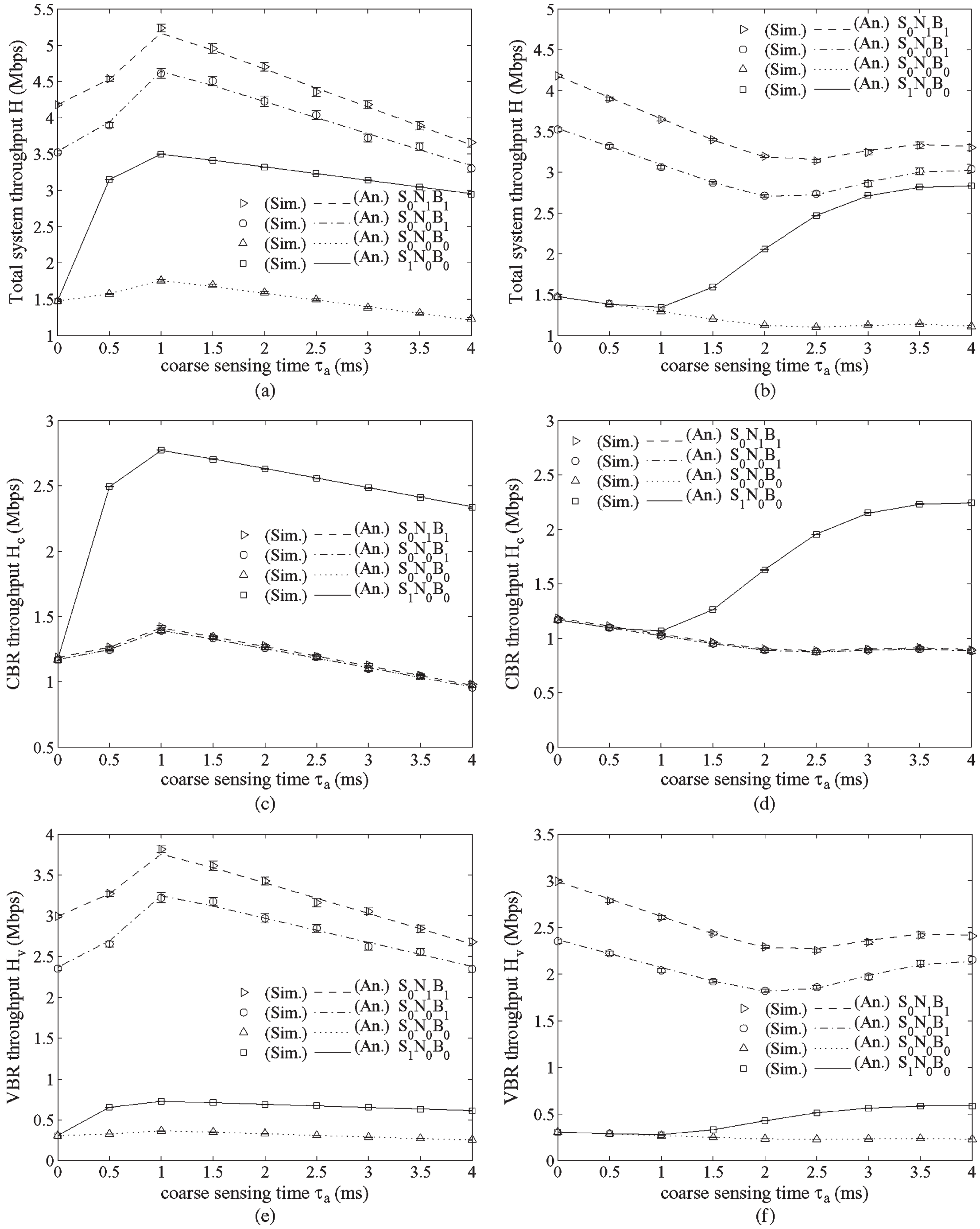


Fig. 6. Throughput of OS-OFDMA implementations. (a) Total with $\gamma = -8$ dB. (b) Total with $\gamma = -12$ dB. (c) CBR, with $\gamma = -8$ dB, as a function of the coarse-sensing time. The parameter setup is the same as in Fig. 5.

Assuming that cochannel interference is uniformly distributed throughout all subchannels, as assumed, for example, in [56], we have varied the SNR at the SU's PU detector (particularly increasing noise floor) caused by the adjacent channel interference and observed the resulting performance for each OS-OFDMA implementation from the perspective of spectrum sensing. Our selected method (treatment of interference as additive noise) is in line with [57] and is considered the most accurate model among all investigated interference models therein. Note that we have not selected other analytical forms of interference description, because they were not applicable for this investigation. For example, the recent work in [58] provides closed-form formulas for the probability of false alarm and misdetection in the presence of noise and impulsive interference, however, without considering SNR of the detected signal, whereas [59] is too detailed and complex to be used in this investigation. We therefore present the following two sets of results: 1) results that consider the increase in noise floor from the optimal value selected in the evaluation so far, i.e., $\gamma = -10$ dB (see Section V-D for detail) and, as a comparison, 2) results that consider the decrease in noise floor from the optimal γ. Note that, as we have stated at the beginning of

Section III, we assume that cochannel interference is easily resolved by the coexistence mechanism.[12]

In Section V-D, we have set the SNR of the PU signal at the SU antenna at $\gamma = -10$ dB, which was considered to represent an interference-free scenario. Obviously, with the SNR 2 dB above the optimal, i.e., $\gamma = -8$ dB, the performance of all OS-OFDMA implementation improves; compare the result in Fig. 6 with the results in Fig. 5. Because of the SNR increase, we see much better performance of two-stage sensing for all OS-OFDMA implementations; see Fig. 6(a), (c), and (f) compared to the results presented in Fig. 5. For $\gamma = -8$ dB, the PU signal is very strong due to low adjacent channel interference, and thus, even using single-stage sensing, the PU cannot be missed. More specifically, a low noise floor contributes to the decrease in false-alarm probability at the coarse sensing stage; see Table III for details.

For $\gamma = -12$ dB, 2 dB below the optimal SNR value assumed for the detected PU signal because of the higher interference caused by the adjacent SU activity, two-stage sensing is always worse than single-stage sensing, except for the $S_1N_0B_0$ implementation. This throughput degradation stems from increased values of false alarm; see the respective values of false alarm for sensing time τ_a in Table III. Due to frequent switching to fine sensing, two-stage sensing will never outperform single-stage sensing. Note that the order in performance for each OS-OFDMA implementation is the same as in Fig. 5; thus, we conclude that interference equally impacts each OS-OFDMA implementation.

Note that the good performance of two-stage sensing in $S_1N_0B_0$, even in the presence of adjacent channel interference, is due to the coarse sensing feature. Because coarse sensing in $S_1N_0B_0$ is performed only for the currently utilized channel (active channel), the SU has a lower probability of switching to the fine-sensing stage for all channels, contrary to other OFDMA implementations, which improves the SU's PU detection performance.

F. Delay Performance of the OS-OFDMA System: A Discussion

Finally, to compliment the analytical results presented in this paper, in this section, we investigate the delay of the OS-OFDMA system considered. To get a realistic estimate of packet delay, we simulated the performance, considering also the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol stack, which exists on top of the MAC and PHY layers of our OS-OFDMA model. To do so, we used the NS-2 model, which we developed, to evaluate the IEEE 802.22 MAC layer [60]. Our NS-2 model is comparable with the OS-OFDMA system with no channel bonding and no subchannel notching; therefore, it represents the $S_1N_0B_0$ case. The most important parameters used in the NS-2 implementation are given in Table IV. For a detailed overview of the IEEE 802.22 NS-2 model, see [60].

In [60], packet delay was studied at the MAC layer, including queuing delays at the BS. Results showed that the PU activity level did not have much impact on the average delay and the sensing strategy used (two or single stage) had no impact on the average delay. To continue our investigation, we study packet delay at the application layer such that delays at all protocol layers in the TCP/IP stack are included.

We study a scenario with four customer premises equipment (CPE) connected to one BS in the IEEE 802.22 network, which applies to a sparsely populated area. In this area, four channels, in total, are not used by the TV broadcasters and are therefore available for the IEEE 802.22 network. Furthermore, there are four WM pairs, corresponding to NPUs in our OS-OFDMA model and each randomly and separately appearing on one of the four channels; hence, the IEEE 802.22 network has to switch channel when a WM appears on the operating channel. The IEEE 802.22 CPE and WM pairs are randomly located within 1 km from the IEEE 802.22 BS. A WM pair consists of a WM transmitter and receiver separated with 150 m. The IEEE 802.22 BS and CPE operate on channels of 6-MHz bandwidth and transmit with 4 W over the whole bandwidth. The WMs operate on a narrower bandwidth of 0.2 MHz, with a transmit power of 200 mW, which, on average, is assumed to be focused on 0.1 MHz of that bandwidth. The antenna gain is set to 0 dB for all devices.

A computer that is connected to the BS through a fixed Ethernet connection (configured with 0-s delay in the simulations) transmits 1500-B packets at a CBR to the four CPE. We want to study the packet delay when the traffic load transmitted to each CPE increases in the range from 0.1 Mb/s to 1 Mb/s. This was done for three different WM activity levels for $1/\mu_n = \{1, 3, 5\}$, whereas the interarrival time was fixed to $1/\lambda_n = 5$.

The average packet delay for all the CPE measured at the MAC layer is presented in Fig. 7(a) and shows that the average measured delay slightly reduces as $1/\mu_n$ increases. This case is because the number of transmitted packets per OFDMA frame increases, because fewer OFDMA frames are utilized due to the reduced probability of obtaining an available channel when the WM idle time increases; hence, the average measure increases. In addition, it is shown that the average delay decreases as the offered load increases, which is because, when the offered load increases, the instantaneous impact from the WMs on the average measured delay reduces. It was found that the throughput reaches plateau at 0.7 Mb/s per CPE, which is the point where the average delay measure becomes stable. We conclude that the average delay at the MAC layer is fairly constant.

Based on the average application-layer packet delay, given in Fig. 7(b), it is shown that the application-layer delay is higher than the MAC-layer delay. Furthermore, it is shown that the delay considerably increases as $1/\mu_n$. This is because more packets are buffered, because the increased number of channel switches increases, and the probability of obtaining an available channel reduces as the WM departure time increases. The reduction in the average application-layer packet delay for $1/\mu_n = 5$ in the traffic load range 0.1–0.4 Mb/s is explained

[12]On the other hand, we want to emphasize that, in this paper, it is, indeed, possible to consider cochannel or adjacent channel interference (if we assume that a coexistence mechanism is absent). It can be done by changing the value of C_p, which is the physical throughput for a single subchannel (described in Section V-A), that depends on the level of interference caused by the coexisting base stations. The calculation of C_p can follow the calculations presented in [16, Sec. IV].

TABLE IV
PARAMETERS FROM SYSTEM PROFILES IN THE IEEE 802.22 STANDARD [5] AND PARAMETERS IN THE NS-2 IMPLEMENTATION OF IEEE 802.22 (ADAPTED FROM [60])

Parameter	IEEE 802.22	NS-2
Bandwidth	{6, 7, 8} MHz	6 MHz
FFT Size	2048	2048
Frequency/Channels	54-698 MHz	575-593 MHz (4 channels)
Frame size	10 ms	10 ms
Duplexing method	TDD	TDD
Tx/Rx Transit Gap (TTG)	83.33/190/270 μs	83.33 μs
Rx/Tx Transit Gap (RTG)	210 μs	210 μs
Modulation types	QPSK,{16,64}-QAM,	16-QAM
Coding rates	1/2, 2/3, 3/4	1/2
Error correction coding	CTC/BTC	No (emulated)
Max power	BS/CPE: 36 dBm	BS/CPE: 36 dBm
Assumed noise figure	BS/CPE: 10 dB	BS/CPE: 10 dB
QoS classes	UGS, rtPS, ErtPS, nrtPS, BE	UGS, BE
Cyclic prefix mode	1/4	1/4
OFDM mapping	DL: vert. UL: horiz.	vert.
Error protection	ARQ	ARQ
Subcarrier spacing	3.348/3.906/4.464 kHz	3.348 kHz
Useful symbol length	298.7/256/224 μs	298.7 μs
Guard time	37.34/32/28 μs	37.34 μs
Symbol duration	373.3/320/280 μs	373.3 μs
Sampling frequency	6.857/8/9.145 MHz	6.857 MHz
Sampling period	0.299/0.256/0.224 ms	0.299 ms
Symbols per frame	26/30/34	26
Used subcarriers	1680	1680
Guard and null subcarriers	368	368
Pilot subcarriers	DL/UL: 240	DL/UL: 240
Data subcarriers	DL/UL: 1440	DL/UL: 1440
Subcarriers/subchannel	DL/UL: 24	DL/UL: 24
Subchannels	DL/UL: 60	DL/UL: 60
Pilot location	Distributed	Distributed
Power control	Distributed	No
Subcarrier allocation	PUSC	PUSC
Sensing strategy	optional	two-stage sensing
Coarse sensing duration	optional	1 ms
Fine sensing duration	optional	30 ms
Fine sensing interval	optional	∞ (event based)
Cooperative sensing	optional	"OR" rule
WM detection threshold	optional	-107 dBm

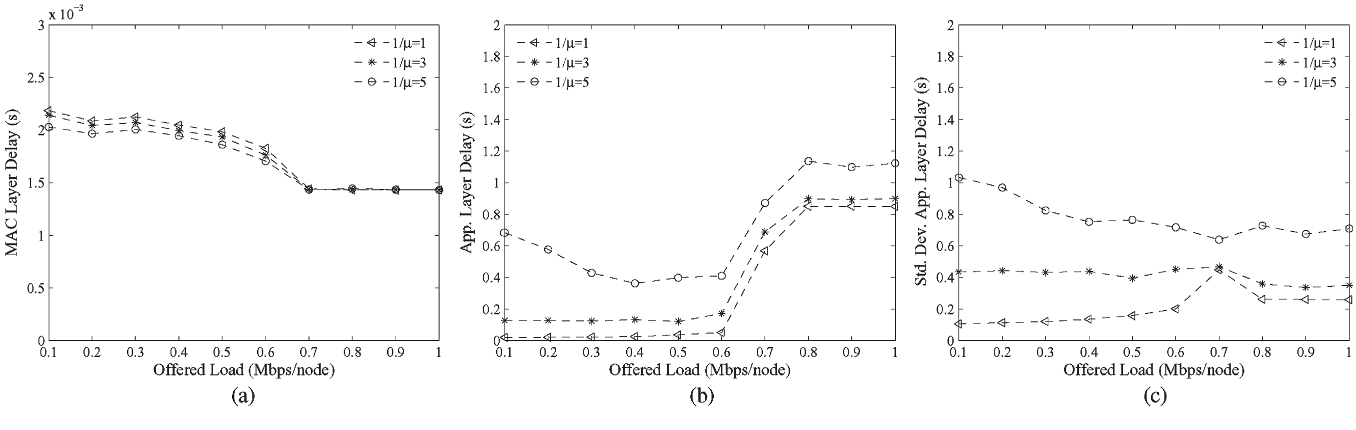


Fig. 7. Results for packet delay analysis with NS-2 simulations. The scenario parameters are given in Section V-F. (a) Average MAC-layer delay. (b) Average application-layer delay. (c) Standard deviation for the application-layer delay.

in the same way as the reduction in the packet delay for the MAC-layer delay. It is also shown that the delay dramatically increases when the offered load is 0.7 Mb/s per CPE, because the full channel capacity is reached, and therefore, the buffering of packets increases. Furthermore, it is shown that the slopes flatten out when the offered load is 0.8 Mb/s, because the buffer is full, and packets starts to drop at the sender's buffer.

The standard deviation for the application-layer delay is given in Fig. 7(c), which shows that the standard deviation increases as the WM departure rate increases, because the number of channel switches increases, and the probability of obtaining an available channel is reduced. In conclusion, it has been shown that the application-layer delay and its deviation are affected by the WM activity level.

VI. Conclusion

In this paper, we have proposed an analytical model that allows the comparison of different designs of OS-OFDMA. We have considered design options that include channel bonding, subchannel notching, and two-stage spectrum sensing. As a performance metric, we have derived the average throughput that was obtained by the SUs of the spectrum, as well as the blocking probability for the CBR service class. In the analysis, we have included the interrelations of different connection classes and priorities, such as the CBR and VBR traffic of the SUs, and wideband and narrowband PUs. We concluded that the OS-OFDMA design that allows the flexible bonding of channels and notching of subchannels that are currently occupied by the PUs obtains the highest throughput compared to the designs that do not consider these options. As one of our numerical results show, the improvement reaches a couple hundred percent when the activity level of the different PU types is very high. In addition, as our investigation shows, the two-stage spectrum sensing technique used in OS-OFDMA proves to increase the average network throughput, provided that the probability of false alarm in the coarse-sensing stage is low. Furthermore, this paper has confirmed that adjacent channel interference reduces the throughput of each OS-OFDMA implementation, whereas OS-OFDM implementation using active channel sensing is the least susceptible to interference. Our delay performance investigations show that temporarily active WMs have a large impact on the obtained delay of OS-OFDMA.

As our future work, we plan to relax some of the assumptions on the activity of wideband and narrowband PUs, e.g., the assumption of the memoryless property of traffic, to see its effect on the performance of OS-OFDMA.

Appendix A
Derivation of $G_x(k|U_x, \lambda_x)$ and $T_x(j|U_x, \mu_x)$

If the interarrival time has a negative exponential distribution with the average arrival rate λ_x, the number of connections generated in a frame of length t_f has a Poisson distribution. However, because we limit the maximum number of users to $U_{x,\max}$, the number of users, including newly generated connections, U_x, cannot exceed $U_{x,\max}$. Considering this condition, we derive the probability of k new connections being generated in a frame $G_x(k|U_x, \lambda_x)$ as

$$G_x(k|U_x,\lambda_x) \triangleq \begin{cases} \frac{(\lambda_x t_f)^k e^{-\lambda_x t_f}}{k!}, & k \geq 0, \\ & U_x < U_{x,\max}, \\ \sum\limits_{i=k}^{\infty} \frac{(\lambda_x t_f)^i e^{-\lambda_x t_f}}{i!}, & k \geq 0, \\ & U_x = U_{x,\max}, \\ 0, & k < 0. \end{cases} \tag{27}$$

Note that the subscript $x = \{w, n, c, v\}$ indicates the class of users, i.e., w for WPU, n for NPU, c for CBR, and v for VBR.

Furthermore, denoting the departure rate of each connection as μ_x, the probability that j connections are released from U_x active connections during a frame of length t_f, $T_x(j|U_x, \mu_x, t_f)$, can recursively be calculated as

$$T_x(j|U_x,\mu_x,t_f) \triangleq \begin{cases} \int_0^{t_f} U_{\mu_x} e^{-U_{\mu_x} t} T_x(j-1| \\ U_x-1, \mu_x, t_f - t)dt, & j > 0 \\ e^{-U_{\mu_x} t_f}, & j = 0 \end{cases} \tag{28}$$

where $U_{\mu_x} = U_x \mu_x$, which, after some manipulation, reduces to

$$T_x(j|U_x,\mu_x,t_f) = \binom{U_x}{j} e^{-U_x \mu_x t_f} (e^{\mu_x t_f} - 1)^j. \tag{29}$$

Because we only consider the connection release probability for users within the duration of a frame, we abbreviate $T_x(j|U_x,\mu_x) \triangleq T_x(j|U_x,\mu_x,t_f)$.

Appendix B
Derivation of $\mathrm{Pr}_{13}(\cdot)$ for $\mathrm{S}_0\mathrm{N}_1\mathrm{B}_1$

In $\mathrm{Pr}_{13}(\cdot)$ in (12), M_e subchannels include M_m subchannels that are occupied by PUs but are misdetected and M_0 subchannels that are correctly detected as idle. Therefore, $M_e = M_m + M_0$, and thus, to calculate $\mathrm{Pr}_{13}(\cdot)$, we define a supporting probability $\mathrm{Pr}_{14}(M_m, M_0|U_w, U_n, S)$, which is the probability that the number of subchannels that were correctly and falsely detected as idle are M_0 and M_m, respectively.

In design option S_0, a SU performs the coarse sensing for all subchannels first, and then, if the SU detects a PU on a subchannel, it immediately switches to fine sensing and again senses all subchannels with high sensing accuracy. Thus, for a condition $S = 0$ (only coarse sensing is performed), the number of subchannels that are detected as idle must be the same as the number of all subchannels, i.e., $M_m + M_0 = M$. In other words, the case $M_m + M_0 < M$ is impossible for the condition $S = 0$. For the condition $S = 2$ (no idle subchannel is detected after all stages of sensing), only the case $M_m + M_0 = 0$ is possible. For $S = 1$, using the detection probability δ_f and the false-alarm probability ϕ_f in the fine-sensing stage, we can derive the probability that M_m busy subchannels are misdetected and M_0 idle subchannels are correctly detected for given U_w WPUs and U_n NPUs. Thus

$$\mathrm{Pr}_{14}(\cdot) \triangleq \begin{cases} F & S = 1, \\ 1 & S = 0, M_m + M_0 = M, \\ & \text{or } S = 2, M_m + M_0 = 0, \\ 0 & S = 0, M_m + M_0 < M, \\ & \text{or } S = 2, M_m + M_0 > 0, \end{cases} \tag{30}$$

where $F = \binom{M_p}{M_m}(1-\delta_f)^{M_m}\delta_f^{M_p - M_m}\binom{M-M_p}{M_0}(1-\phi_f)^{M_0} \times \phi_f^{M-M_p-M_0}$, and $M_p = \min(M, U_w l_w + U_n l_n)$ is the number of subchannels that are, in fact, occupied by PUs. Therefore, $\mathrm{Pr}_{13}(\cdot)$ can be derived as

$$\mathrm{Pr}_{13}(\cdot) \triangleq \sum_{x=0}^{M_e} \mathrm{Pr}_{14}(x, M_e - x|U_w, U_n, S). \tag{31}$$

APPENDIX C
DERIVATION OF $\mathrm{Pr}_{15}(\cdot)$ FOR $\mathrm{S}_0\mathrm{N}_1\mathrm{B}_1$

To derive $\mathrm{Pr}_{15}(\cdot)$, we need to consider the following three cases. First, if the OSA network misdetects existing PUs and correctly detects all idle subchannels in the coarse-sensing stage, $S = 0$, because the OSA network will not advance to fine sensing. Second, if the OSA network correctly or falsely detects at least one PU in the coarse-sensing stage and also correctly or falsely detects all subchannels as busy in the fine-sensing stage, $S = 2$, because after coarse and fine sensing, no idle subchannel is detected. Otherwise, $S = 1$. Thus

$$\mathrm{Pr}_{15}(\cdot) \triangleq \begin{cases} (1-\delta_a)^{M_p}(1-\phi_a)^{M-M_p}, & S=0, \\ \left(1-(1-\delta_a)^{M_p}(1-\phi_a)^{M-M_p}\right) & \\ \quad \times \delta_f^{M_p}\phi_f^{M-M_p}, & S=2, \\ 1-\mathrm{Pr}_{15}(S=0|U_w,U_n) & \\ \quad -\mathrm{Pr}_{15}(S=2|U_w,U_n), & S=1. \end{cases} \tag{33}$$

APPENDIX D
DERIVATION OF $\mathrm{Pr}_{13}(\cdot)$ FOR $\mathrm{S}_0\mathrm{N}_0\mathrm{B}_1$

For the case $\mathrm{S}_0\mathrm{N}_0\mathrm{B}_1$, because the spectrum is utilized based on the unit of bandwidth of one channel rather than one subchannel, we introduce the probability of the number of channels detected as idle X_a to calculate the probability of the number of subchannels detected as idle M_e. Denoting $\mathrm{Pr}_{20}(X_a|U_w,U_n,S)$ as the probability that the number of channels detected as idle is X_a, given U_w WPUs and U_n NPUs in the S sensing stage, (31) is modified as

$$\mathrm{Pr}_{13}(\cdot) \triangleq \begin{cases} \mathrm{Pr}_{20}(X_a|U_w,U_n,S), & M_a = X_aY, \\ 0, & \text{otherwise.} \end{cases} \tag{34}$$

There are two required conditions for $\mathrm{Pr}_{20}(\cdot)$ in (34). First, the sum of the channels detected as idle and the number of WPUs cannot be greater than the total number of channels, i.e., $X_a + U_w \leq X$. Second, the number of NPUs cannot be greater than the total number of subchannels that are not occupied by the WPUs, i.e., $U_n \leq (X-U_w)\lfloor Y/l_n \rfloor$. We denote $\mathbf{1}_c$ as an indicator of these conditions, defining $\mathbf{1}_c = 1$ for $X_a + U_t \leq X$ or $U_n \leq (X-U_w)\lfloor Y/l_n \rfloor$; otherwise, $\mathbf{1}_c = 0$.

Next, we calculate $\mathrm{Pr}_{20}(\cdot)$ under the feasible conditions, considering different sensing stages. Under the condition that no channel is detected as idle after the fine sensing, i.e., $S = 2$, the number of channels detected as idle is $X_a = 0$, under the assumption of perfect PU detection. On the other hand, when all channels are detected as idle in the coarse sensing, i.e., $S = 0$, only $X_a = X$ is possible. The analysis for the condition that the SU performs fine sensing and detects idle channels, i.e., $S = 1$, is not easy to directly derive, because the number of channels detected as idle depends on the position of NPUs in the spectrum and the number of NPUs. Thus, defining the number of channels that are, in fact, occupied by the NPU as X_n, we deconstruct $\mathrm{Pr}_{20}(\cdot)$ for $S = 1$ into the following two components: 1) the conditional probability of X_n for a given number of PUs and the sensing stage, denoted as $\mathrm{Pr}_{21}(X_n|U_w,U_n,S)$, and 2) the conditional probability of the number of channels detected as idle for a given X_n, denoted as $\mathrm{Pr}_{22}(X_a|X_n,U_w,U_n,S)$. Then, Pr_{20} is given in (34), shown at the bottom of the page, where $\mathcal{X} = \{X_n | \lceil (U_n l_n/Y \rceil \leq X_n \leq \min(U_n, X-U_t-X_a)\}$, because X_n is the smallest when all NPUs are located on adjacent subchannels, i.e., $\lceil (U_n l_n)/Y \rceil$, and the largest when all NPUs are located in different channels that are separated as far as possible, i.e., $\min(U_n, X-U_t-X_a)$.

To calculate $\mathrm{Pr}_{21}(\cdot)$ in (32) given at the bottom of the page, we assume that any NPU can appear on any subchannel with equal probability and that false alarms can uniformly occur over all idle subchannels. Then, we introduce a supporting function $f_s(k,x,r)$, which denotes the number of possibilities that k items are distributed over exactly x bins, each of which has a capacity of r items.

To derive $f_s(k,x,r)$, first, we introduce the supporting variable i_j, i.e., the number of items in the jth bin, where $j \in \{1,\ldots,x\}$. Then, there can be $\binom{r}{i_j}$ possible distributions for the jth bin, and thus, for x bins, there can be $\sum_{j=1}^{i_1}\binom{r}{j}\cdots\sum_{j=1}^{i_x}\binom{r}{j}$ possibilities. Because there should be no empty bin, $i_j \geq 1$. In addition, each of the bins has a capacity of r items, and the total number of items cannot be greater than k, and therefore, $i_j \leq \min(r,k)$. In addition, if the number of bins is less than the number of items or equal to zero, there is no way of filling all x bins. Thus

$$f_s(k,x,r) = \begin{cases} \dfrac{\sum_{\mathcal{I}(k,x,r)}\sum_{j=1}^{i_1}\binom{r}{j}}{\cdots\sum_{j=1}^{i_x}\binom{r}{j}}, & 0<x<k, \\ 0, & \text{otherwise,} \end{cases} \tag{35}$$

where $\mathcal{I}(k,x,r) = \{i_1,\ldots,i_x | \sum_{j=1}^{x} i_j = k, i_1,\ldots,i_x \in \{1,\ldots,\min(r,k)\}\}$.

Then, $\mathrm{Pr}_{21}(\cdot)$ can be calculated by dividing the number of possible events that U_n NPUs are located on exactly X_n channels, each of which can have at maximum $\lfloor Y/l_n \rfloor$ NPUs, i.e., $f_s(U_n, X_n, \lfloor Y/l_n \rfloor)$, by the number of all possible events that U_n NPUs appear on $X - U_w$ channels, i.e., $\binom{(X-U_w)\lfloor Y/l_n \rfloor}{U_n}$. Note that, if there is no NPU, i.e., $U_n = 0$, then X_n should be zero. Considering the possible case of selecting X_n NPU channels from a total of $X - U_w$ channels, i.e., $\binom{X-U_w}{X_n}$, we derive $\mathrm{Pr}_{21}(\cdot)$ as

$$\mathrm{Pr}_{21}(\cdot) = \begin{cases} 1, & X_n = 0, U_n = 0, \\ \dfrac{\binom{X-U_w}{X_n} f_s(U_n, X_n, \lfloor Y/l_n \rfloor)}{\binom{(X-U_w)\lfloor Y/l_n \rfloor}{U_n}}, & \text{otherwise.} \end{cases} \tag{36}$$

$$\mathrm{Pr}_{20}(\cdot) \triangleq \begin{cases} \sum_{\mathcal{X}} \mathrm{Pr}_{21}(X_n|U_w,U_n,S)\,\mathrm{Pr}_{22}(X_a|X_n,U_w,U_n,S), & \mathbf{1}_c = 1, S = 2, \\ 1, & \mathbf{1}_c = 1, \text{ and } S = 0, X_a = X \text{ or } S = 2, X_a = 0, \\ 0, & \text{otherwise.} \end{cases} \tag{32}$$

$$\mathrm{Pr}_{23}(\cdot) \triangleq \begin{cases} \mathrm{Pr}_{24}\left(X_a^{(t)}|X_a^{(t-1)}, U_w^{(t)}, U_w^{(t-1)}, U_n^{(t)}, U_n^{(t-1)}, S^{(t)}, S^{(t-1)}\right), & M_a = X_a Y \\ 0, & \text{otherwise} \end{cases} \tag{37}$$

$$\mathrm{Pr}_{24}(\cdot) \approxeq \begin{cases} 1, & U_w^{(t)} = U_w^{(t-1)}, U_n^{(t)} = U_n^{(t-1)}, X_a^{(t)} = X_a^{(t-1)} \\ 0, & U_w^{(t)} = U_w^{(t-1)}, U_n^{(t)} = U_n^{(t-1)}, X_a^{(t)} \neq X_a^{(t-1)} \\ \mathrm{Pr}_{20}(X_a|U_w, U_n, S), & \text{otherwise} \end{cases} \tag{38}$$

Now, we present the derivation of $\mathrm{Pr}_{22}(\cdot)$ in (32). If there exist U_w and X_n channels that are occupied by WPUs and NPUs, respectively, and X_a channels are correctly detected as idle, the remaining $X - U_w - X_n - X_a$ channels must falsely be detected as busy. Considering the number of events of selecting X_a channels from $X - U_w - X_n$ idle channels, we derive $\mathrm{Pr}_{22}(\cdot)$ as

$$\mathrm{Pr}_{22}(\cdot) = \binom{X - U_w - X_n}{X_a} \left(1 - (1 - \phi_f)^Y\right)^{X - U_w - X_n - X_a} \times (1 - \phi_f)^{Y X_a}. \tag{39}$$

APPENDIX E
DERIVATION OF $\mathrm{Pr}_{23}(\cdot)$ FOR $\mathrm{S_0N_0B_1}$

Because, for $\mathrm{S_0N_0B_1}$, the spectrum is utilized based on the unit of bandwidth of one channel, denoting a supporting probability $\mathrm{Pr}_{24}(X_a^{(t)}|X_a^{(t-1)}, U_w^{(t)}, U_w^{(t-1)}, U_n^{(t)}, U_n^{(t-1)}, S^{(t)}, S^{(t-1)})$ as the conditional probability of the number of channels, we derive $\mathrm{Pr}_{23}(\cdot)$ as in (37), shown at the top of the page.

To reduce the complexity of calculating $\mathrm{Pr}_{24}(\cdot)$, we use an approximation that, if the number of PUs is the same at times t and $t-1$, the positions of NPUs at times t and $t-1$ are also the same. This approximation is valid when the PU activity is not high. With this approximation, we ignore the case that a certain number of NPUs disappear, whereas at the same time, the same number of new NPUs appear, but at different locations. In addition, we assume that, if the number of WPUs and NPUs have changed, the number of channels detected as idle is independent of the number of WPUs and NPUs at time $t-1$, which means that $\mathrm{Pr}_{24}(\cdot) \approxeq \mathrm{Pr}_{20}(\cdot)$. Considering these approximations, we derive $\mathrm{Pr}_{24}(\cdot)$ as in (38), shown at the top of the page, where $\mathrm{Pr}_{20}(\cdot)$ is defined in Appendix D as (32).

APPENDIX F
DERIVATION OF $\mathrm{Pr}_{15}(\cdot)$ FOR $\mathrm{S_0N_0B_1}$

To modify $\mathrm{Pr}_{15}(\cdot)$ in (33), under the approximation of the perfect detection, depending on the number of subchannels occupied by PUs, i.e., M_p, we consider three cases. In the first case, $M_p = M$, all subchannels are occupied by PUs. Then, because of the perfect detection approximation, $S = 2$ is the only feasible condition. In the second case, $M_p = 0$, no PU appears on the subchannels. In this case, the false-alarm probability of each sensing stage affects the probability $\mathrm{Pr}_{15}(\cdot)$. In the last case, $0 < M_p < M$, the probability of $S = 0$ is zero, and the false-alarm probability of the coarse sensing does not affect the performance. Thus

$$\mathrm{Pr}_{15}(\cdot) = \begin{cases} 1, & M_p = M, S = 2, \\ (1-\phi_a)^M, & M_p = 0, S = 0, \\ 1 - (1-\phi_a)^M \\ \quad -\phi_a^M (\phi_f)^M, & M_p = 0, S = 1, \\ \phi_a^M \phi_f^M, & M_p x = 0, S = 2, \\ 1 - \phi_f^{M - M_p}, & 0 < M_p < M, S = 1, \\ \phi_f^{M - M_p}, & 0 < M_p < M, S = 2, \\ 0, & \text{otherwise.} \end{cases} \tag{40}$$

REFERENCES

[1] J. Park, P. Pawełczak, P. Grønsund, and D. Čabrić, "Performance of opportunistic spectrum OFDMA network with users of different priorities and traffic characteristics," in *Proc. IEEE GLOBECOM*, Miami, FL, Dec. 6–10, 2010, pp. 1–6.
[2] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access: Signal processing, networking, and regulatory policy," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 79–89, May 2007.
[3] Y.-C. Liang, K.-C. Chen, G. Y. Li, and P. Mähönen, "Cognitive radio networking and communications: An overview," *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3386–3407, Sep. 2011.
[4] T. A. Weiss and F. K. Jondral, "Spectrum pooling: An innovative strategy for the enhancement of spectrum efficiency," *IEEE Commun. Mag.*, vol. 42, no. 3, pp. S8–S14, Mar. 2004.
[5] *Standard for Wireless Regional Area Networks—Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands*, IEEE Std. 802.22, Jul. 2011.
[6] *The Network Simulator NS-2*. [Online]. Available: http://www.isi.edu/nsnam/ns/
[7] A. E. Leu, B. L. Mark, and M. A. McHenry, "A framework for cognitive WiMAX frequency agility," *Proc. IEEE*, vol. 97, no. 4, pp. 755–773, Apr. 2009.
[8] L. Song, C. Feng, Z. Zeng, and X. Zhang, "Research on WRAN system-level simulation platform design," in *Proc. ICST Chinacom*, Hangzhou, China, Aug. 25–27, 2008, pp. 595–599.
[9] H.-S. Chen, W. Gao, and D. G. Daut, "Spectrum sensing using cyclostationary properties and application to IEEE 802.22 WRAN," in *Proc. IEEE GLOBECOM*, Washington, DC, Nov. 26–30, 2007, pp. 3133–3138.
[10] Y.-J. Choi and K. G. Shin, "Opportunistic access of TV spectrum using cognitive-radio-enabled cellular network," *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3853–3864, Oct. 2011.
[11] J. Park, T. Song, J. Hur, S. M. Lee, J. Choi, K. Kim, K. Lim, C.-H. Lee, H. Kim, and J. Laskar, "A fully integrated UHF-band CMOS receiver with multiresolution spectrum sensing (MRSS) functionality for IEEE 802.22

cognitive radio applications," *IEEE J. Solid-State Circuits*, vol. 44, no. 1, pp. 258–268, Jan. 2009.

[12] H. Kim, J. Kim, S. Yang, M. Hong, and Y. Shin, "An effective MIMO-OFDM system for IEEE 802.22 WRAN channels," *IEEE Trans. Circuits Syst. II*, vol. 55, no. 8, pp. 821–825, Aug. 2008.

[13] D. Niyato, E. Hossain, and Z. Han, "Dynamic spectrum access in IEEE-802.22-based cognitive wireless networks: A game-theoretic model for competitive spectrum bidding and pricing," *IEEE Wireless Commun. Mag.*, vol. 16, no. 2, pp. 16–23, Apr. 2009.

[14] Y.-C. Liang, A. T. Hoang, and H.-H. Chen, "Cognitive radio on TV bands: A new approach to prove wireless connectivity for rural areas," *IEEE Wireless Commun. Mag.*, vol. 15, no. 3, pp. 16–22, Jun. 2008.

[15] S. Segupta, M. Chatterje, and R. Chandramouli, "A coordinated distributed scheme for cognitive-radio-based IEEE 802.22 wireless mesh networks," in *Proc. IEEE CogNet/ICC Workshop*, Beijing, China, May 19–23, 2008, pp. 461–465.

[16] S.-E. Elayoubi and B. Fouresité, "Performance evaluation of admission control and adaptive modulation in OFDMA WiMax systems," *IEEE/ACM Trans. Netw.*, vol. 16, no. 5, pp. 1200–1211, Oct. 2008.

[17] T. Luo, W. Xiang, and H.-H. Chen, "A subcarrier allocation scheme for cognitive radio systems based on multicarrier modulation," *IEEE Trans. Wireless Commun.*, vol. 7, no. 9, pp. 3335–3340, Sep. 2008.

[18] Y. Xing, R. Chandramouli, S. Mangold, and N. S. Shankar, "Dynamic spectrum access in open spectrum wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 626–637, Mar. 2006.

[19] C.-T. Chou, S. Shankar, H. Kim, and K. G. Shin, "What and how much to gain by spectrum agility?" *IEEE J. Sel. Areas Commun.*, vol. 25, no. 3, pp. 576–588, Apr. 2007.

[20] J. Park, P. Pawełczak, and D. Čabrić, "Performance of joint spectrum sensing and MAC algorithms for multichannel opportunistic spectrum access ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 7, pp. 1011–1027, Jul. 2011.

[21] C. R. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. J. Shellhammer, and W. Caldwell, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 130–138, Jan. 2009.

[22] Y.-C. Liang, Y. Zeng, E. C. Peh, and A. T. Hoang, "Sensing throughput tradeoff in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326–1337, Apr. 2008.

[23] A. T. Hoang, Y.-C. Liang, D. T. C. Wong, Y. Zeng, and R. Zhang, "Opportunistic spectrum access for energy-constrained cognitive radios," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1206–1211, Mar. 2009.

[24] P. Papadimitratos, S. Sankaranarayanan, and A. Mishra, "A bandwidth-sharing approach to improve licensed spectrum utilization," *IEEE Commun. Mag.*, vol. 43, no. 12, pp. S10–S14, Dec. 2005.

[25] Y. Zhang and C. Leung, "A distributed algorithm for resource allocation in OFDM cognitive radio systems," *IEEE Trans. Veh. Technol.*, vol. 60, no. 2, pp. 546–554, Feb. 2011.

[26] P. Cheng, Z. Zhang, H. Huang, and P. Qiu, "A distributed algorithm for optimal resource allocation in cognitive OFDMA systems," in *Proc. IEEE ICC*, Beijing, China, May 19–23, 2008, pp. 4718–4723.

[27] Y. Zhang and C. Leung, "Resource allocation for non-real-time services in OFDM-based cognitive radio systems," *IEEE Commun. Lett.*, vol. 13, no. 1, pp. 16–18, Jan. 2009.

[28] S. Geirhofer, L. Tong, and B. M. Sandler, "Dynamic spectrum access in the time domain: Modeling and exploiting white space," *IEEE Commun. Mag.*, vol. 45, no. 5, pp. 66–72, May 2007.

[29] S. Huang, X. Liu, and Z. Ding, "Optimal sensing-transmission structure for dynamic spectrum access," in *Proc. IEEE INFOCOM*, Rio De Janeiro, Brazil, Apr. 19–25, 2009, pp. 2295–2303.

[30] J. Gambini, O. Simeone, Y. Bar-Ness, U. Spagnolini, and T. Yu, "Packet-wise vertical handover for unlicensed multistandard spectrum access with cognitive radios," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 5172–5176, Dec. 2008.

[31] V. K. Tumuluru, P. Wang, and D. Niyato, "A novel spectrum-scheduling scheme for multichannel cognitive radio network and performance analysis," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1849–1858, May 2011.

[32] Y.-Y. Lin and K.-C. Chen, "Asynchronous dynamic spectrum access," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 222–236, Jan. 2012.

[33] P. Van Mieghem, *Performance Analysis of Communications Networks and Systems*. Cambridge, U.K.: Cambridge Univ. Press, 2006.

[34] M. Wellens, J. Riihijärvi, and P. Mähönen, "Empirical time- and frequency-domain models of spectrum use," *Phys. Commun.*, vol. 2, no. 1/2, pp. 10–32, Mar.–Jun. 2009.

[35] L. Luo, N. M. Neihart, S. Roy, and D. J. Allstot, "A two-stage sensing technique for dynamic spectrum access," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 3028–3037, Jun. 2009.

[36] W. S. Jeon and D. G. Jeong, "An advanced quiet-period management scheme for cognitive radio systems," *IEEE Trans. Veh. Technol.*, vol. 59, no. 3, pp. 1242–1256, Mar. 2010.

[37] W. Gabran, P. Pawełczak, and D. Čabrić, "Throughput and collision analysis for multichannel multistage spectrum sensing algorithms," *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3309–3323, Sep. 2011.

[38] W. S. Jeon, D. G. Jeong, J. A. Han, G. Ko, and M. S. Song, "An efficient quiet period management scheme for cognitive radio systems," *IEEE Trans. Wireless Commun.*, vol. 7, no. 2, pp. 505–509, Feb. 2008.

[39] E. Rebeiz, V. Jain, and D. Cabric, "Cyclostationarity-based low-complexity wideband spectrum sensing using compressive sampling," in *Proc. IEEE ICC*, Ottawa, ON, Canada, Jun. 10–15, 2012.

[40] M. Mishali and Y. C. Eldar, "From theory to practice: Sub-Nyquist sampling of sparse wideband analog signals," *IEEE J. Sel. Topics Signal Process.*, vol. 4, no. 2, pp. 375–391, Apr. 2010.

[41] Y. L. Polo, Y. Wang, A. Pandharipande, and G. Leus, "Compressive wideband spectrum sensing," in *Proc. IEEE ICASSP*, Taipei, Taiwan, Apr. 19–24, 2009, pp. 2337–2340.

[42] Z. Tian and G. B. Giannakis, "Compressed sensing for wideband cognitive radios," in *Proc. IEEE ICASSP*, Honolulu, HI, Apr. 15–20, 2007, pp. IV-1357–IV-1360.

[43] "In the matter of ET Docket no. 04-18 and ET Docket no. 02-38 second report and order and memorandum opinion and order," Fed. Commun. Comm., Washington, DC, Tech. Rep. 08-260, Nov. 14, 2008.

[44] D. Qu, Z. Wang, and T. Jiang, "Extended active interference cancellation for sidelobe suppression in cognitive radio OFDM systems with cyclic prefix," *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1689–1695, May 2010.

[45] Z. Yuan and A. M. Wyglinski, "On sidelobe suppression for multicarrier-based transmission in dynamic spectrum access networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1998–2006, May 2010.

[46] P. Sutton, B. Özgül, I. Macaluso, and L. Doyle, "OFDM pulse-shaped waveforms for dynamic spectrum access," in *Proc. IEEE DySPAN*, Singapore, Apr. 6–9, 2010, pp. 1–2.

[47] S. Sharma, N. Zhu, and T.-C. Chiueh, "Low-latency mobile IP handoff for infrastructure-mode wireless LAN," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 4, pp. 643–652, May 2004.

[48] A. Raniwala and T.-C. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multichannel wireless mesh network," in *Proc. IEEE INFOCOM*, Miami, FL, Mar. 12–17, 2005, pp. 2223–2234.

[49] J. Park, P. Pawełczak, P. Grønsund, and D. Čabrić, Analysis framework for opportunistic spectrum OFDMA and its application to the IEEE 802.22 standard. [Online]. Available: http://arxiv.org/abs/1007.5080

[50] E. Reihl, "Wireless microphone characteristics," IEEE, Piscataway, NJ, Tech. Rep. 802.22-06/0070r0, May 2006.

[51] D. Lam, D. C. Cox, and J. Widom, "Teletraffic modeling for personal communication services," *IEEE Commun. Mag.*, vol. 35, no. 2, pp. 79–87, Feb. 1997.

[52] *Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Technical Characteristics for Professional Wireless Microphone Systems (PWMS); System Reference Model*, ETSI Std. TR 102 546 v1.1.1, Apr. 2007.

[53] H.-S. Chen and W. Gao, "Spectrum sensing for TV white space in North America," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 2, pp. 316–326, Feb. 2011.

[54] S. M. Almalfouh and G. L. Stüber, "Interference-aware radio resource allocation in OFDMA-based cognitive radio network," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1699–1713, May 2011.

[55] D. T. Ngo and T. Le-Ngoc, "Distributed resource allocation for cognitive radio networks with spectrum-sharing constraints," *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3436–3449, Sep. 2011.

[56] M. K. Karray, "Analytical evaluation of QoS in the downlink of OFDMA wireless cellular networks serving streaming and elastic traffic," *IEEE Trans. Wireless Commun.*, vol. 9, no. 5, pp. 1799–1807, May 2010.

[57] A. Iyer, C. Rosenberg, and A. Karnik, "What is the right model for wireless channel interference?" *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2662–2671, May 2009.

[58] T. Trump and I. Müürsepp, "An energy detector for spectrum sensing in impulsive noise environment," in *Proc. IEEE PIMRC*, Toronto, ON, Canada, Sep. 11–14, 2011, pp. 467–471.

[59] K. F. McDonald and R. S. Blum, "A statistical and physical mechanisms-based interference and noise model for array observations," *IEEE Trans. Signal Process.*, vol. 48, no. 7, pp. 2044–2056, Jul. 2000.

[60] P. Grønsund, P. Pawełczak, J. Park, and D. Cabric, "System-level performance of IEEE 802.22 with sensing-based detection of wireless microphones," Oct. 2011, submitted for publication.

Jihoon Park received the M.Sc. degree in electrical engineering from Sogang University, Seoul, Korea, in 1998 and the Ph.D. degree in electrical engineering from the University of California, Los Angeles, in 2010.

From 1998 to 2005, he was a member of the Mobile Terminal R&D Department, Samsung Electronics Company, Seoul, where he developed software for more than 20 commercial Samsung cell phones, including the world's first IS-2000 cell phone and the first Korean wideband code division multiple access cell phone. He is currently with the R&D Team, Mobile Communication Division, Samsung Electronics Company, Gyeonggi, Korea. His research interest is focused on the cross-layer modeling methods of practical opportunistic spectrum access networks.

Przemysław Pawełczak (S'03–M'10) was born in Tomaszów Lubelski, Poland, in 1980. He received the M.Sc. degree from Wrocław University of Technology, Wrocław, Poland, in 2004 and the Ph.D. degree from Delft University of Technology, Delft, The Netherlands.

From 2004 to 2005, he was a Staff Member with the Siemens COM Software Development Center, Wrocław. During Fall 2007, he was a Visiting Scholar with the Connectivity Laboratory, University of California, Berkeley. From 2009 to 2011 he was a Postdoctoral Researcher with the Cognitive Reconfigurable Embedded Systems Laboratory, Department of Electrical Engineering, University of California, Los Angeles. He is currently a Research Staff Member with the Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Berlin, Germany. His research interests include the cross-layer analysis of opportunistic spectrum access networks.

Dr. Pawełczak was a Vice-Chair of the IEEE SCC41 Standardization Committee between 2009 and 2011. He was a Coordinator and an Organizing Committee Member of cognitive radio workshops collocated with the IEEE International Conference on Communications in 2007, 2008, and 2009 and an Organizing Committee Member of the Association for Computing Machinery SIGMOBILE Workshop on Cognitive Wireless Networking. Since 2010 he has been a Cochair of the Demonstration Track of the IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks. He was nominated for the 2011 UCLA Chancellor Award for Postdoctoral Research, and he was the recipient of the Annual Telecom Prize for Best Ph.D. Student in Telecommunications in The Netherlands from the Dutch Royal Institute of Engineers in 2008.

Pål Grønsund was born in Flekkefjord, Norway. He received the M.Sc. degree in informatics from the University of Oslo, Oslo, Norway, in 2007. He is currently working toward the Ph.D. degree in cognitive radio and dynamic spectrum access with the Department of Informatics, University of Oslo, in collaboration with Telenor, Fornebu, Norway, and Simula Research Laboratory, Fornebu.

Since 2007, he has been a Research Scientist with Telenor, where he first gained practical and theoretical experience with trials and performance evaluation of future and heterogeneous IEEE 802.16, IEEE 802.11, and Third-Generation Partnership Project (3GPP) networks. In Fall 2010, he was a Visiting Researcher with the Cognitive Reconfigurable Embedded Systems Laboratory, University of California, Los Angeles. His research interests include cognitive radio, Long-Term Evolution, WiMAX, femtocells, and heterogeneous networks. He has experience from various international projects on cognitive radio within the European Commission framework programs.

Danijela Cabric received the Dipl. Ing. degree from the University of Belgrade, Belgrade, Serbia, in 1998, the M.Sc. degree in electrical engineering from the University of California, Los Angeles, in 2001, and the Ph.D. degree in electrical engineering from the University of California, Berkeley, in 2007.

She was a Member of the Berkeley Wireless Research Center, University of California, Berkeley. In 2008, she joined the faculty of the Department of Electrical Engineering, University of California, Los Angeles, as an Assistant Professor. She has written three book chapters and more than 20 five major journal papers and conference proceedings in wireless communications and circuits and embedded systems. Her research interests include novel radio architecture, signal processing, and networking techniques to implement spectrum sensing functionality in cognitive radios.

Dr. Cabric received the Samueli Fellowship in 2008, the Okawa Foundation Research Grant in 2009, and the National Science Foundation Faculty Early Career Development Award in 2012.

Paper I
Spectrum Sensing Aided Long-Term Spectrum Management in Cognitive Radio Networks

Pål Grønsund, Paal E. Engelstad, Przemysław Pawełczak, Ole Grøndalen, Per H. Lehne and Danijela Čabrić

Submitted to IEEE Conference on Local Computer Networks (LCN), Sydney, Australia, Oct. 21-24, 2013.

Spectrum Sensing Aided Long-Term Spectrum Management in Cognitive Radio Networks

Pål Grønsund*†, Paal E. Engelstad†‡, Przemysław Pawełczak§, Ole Grøndalen*, Per H. Lehne* and Danijela Cabric¶
*Telenor, Snarøyveien 30, 1331 Fornebu, Norway
†University of Oslo, Gaustadallen 23, 0373 Oslo, Norway
‡Oslo and Akershus University College of Applied Sciences, Pilestredet 46, 0130 Oslo, Norway
§Delft University of Technology, Mekelweg 4, 2600 GA Delft, The Netherlands
¶University of California, Los Angeles, 56-125B Engineering IV Building, Los Angeles, CA 90095-1594, USA
Email: {pal.gronsund,ole.grondalen,per-hjalmar.lehne}@telenor.com; {paalrgr,paalee}@ifi.uio.no;
paal.engelstad@hioa.no; p.pawelczak@tudelft.nl; danijela@ee.ucla.edu

***Abstract*—Wireless microphones operating in the TV white spaces often appear at specific venues such as schools or churches, and at specific times. Hence, their location and appearance pattern can be predicted from spectrum sensing statistics. In this paper we propose and evaluate three spectrum selection functions that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection in IEEE 802.22 network to enhance performance by reducing interference and increasing throughput. To evaluate performance of the spectrum selection functions, these are implemented in a detailed system level simulator for the cognitive radio standard IEEE 802.22. We find that the spectrum selection function that uses statistics about channel idle and busy periods performs best when primary user activity is high, and that the spectrum selection function that uses predictions about location and distance to primary users performs best when cognitive radio users are mobile and the primary user activity is low.**

I. Introduction

The IEEE 802.22 [1] standard is the first technical standard to provide a broadband service by operating in the TV white spaces [2]. IEEE 802.22 devices use geo-location and communicate with a database [3] to obtain information about available frequencies and allowed transmit power levels at their locations. In addition IEEE 802.22 devices can use sensing techniques to detect sudden appearances of primary users, such as TV transmitters and wireless microphones (WMs). TV broadcasters update the database with their frequency usage and transmit power levels at all locations. Other low power devices operating in these bands, such as WMs, might update the database, but might also appear suddenly without notification. Detection and protection of these WMs are considered to be a great challenge that can be handled by using sensing techniques to detect WMs and then switch to a vacant channel.

The spectrum management, which aims at exploiting white space channels while protecting the primary users, is usually executed on short time scales according to cognitive radio standards, such as IEEE 802.22. In this paper, however, we propose and evaluate spectrum management functions executed on longer time scales, based on the historical record of existing short-term measurements. This new spectrum management approach is not specified in the IEEE 802.22 standard. The new spectrum management functions reduce interference and increase throughput by working complementary to the existing short-term spectrum management functions, instead of replacing them.

Three spectrum selection (SSE) functions for long-term spectrum management are proposed and evaluated according to the following hypotheses; H.1: *SSE-Distance* will improve performance when the cognitive radio terminals are mobile by selecting the channel with the longest expected distance to the nearest WM. This is motivated by the fact that WMs often appear at specific locations in venues such as schools and churches. H.2: *SSE-OnOff* will improve performance when WM activity is high by selecting the channel with highest probability of being available. This is motivated by the fact that WMs often appear at specific time intervals such as each morning, evening or Sunday. Finally, H.3: *SSE-Hybrid* combine the former two to use the optimal SSE function depending on spectrum usage statistics. Both the expected distance to the WMs in *SSE-Distance* and the expected channel availability in *SSE-OnOff* are predicted based on the historical record of short-term sensor measurements.

To evaluate performance of the SSE functions, we extend a comprehensive implementation of the IEEE 802.22 stack in the NS-2 simulator. Our simulation model has been used to evaluate different QoS profiles in IEEE 802.22 with applications such as video and voice in [4], delay over IEEE 802.22 in [5], different sensing strategies in [6] and varying spatial and temporal impact of WM activity on the IEEE 802.22 network in [7]. In this paper, we extend the simulator with an implementation of the proposed SSE functions. Further, the terminals are mobile as opposed to fixed in our previous work [4]–[7]. A brief description of the simulation model is given in this paper. For more details on specific functionality, the reader is referred to [4]–[7], while noting that certain parts of earlier text appearing in [4]–[7] is repeated here, where necessary, to introduce features of our simulator.

A related simulation model on MAC layer performance of IEEE 802.22 is found in [8], [9], but the complete IEEE 802.22

Parts of this work was supported by the European Community FP7 program under grant agreement 248454 (QoSMOS).

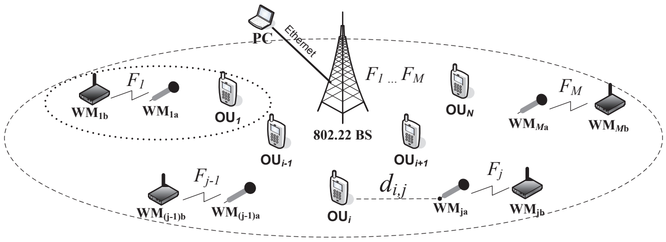


Fig. 1. Illustration of the IEEE 802.22 network model.

stack is not implemented. Similar functions to *SSE-OnOff* are proposed and studied in [10]–[14] and to *SSE-Distance* in [15]. The novelty in this paper is the proposal to use such spectrum selection functions to complement the existing spectrum management framework and spectrum sensing schemes in IEEE 802.22 with the specific application to WM as the primary user. This enable the performance evaluation of these functions for several metrics such as throughput, packet loss, delay, and interference to both the IEEE 802.22 system and the WM. To the best of our knowledge, this has not been done before. Note that this paper is a completely new contribution in the series of our earlier works on IEEE 802.22.

This paper is organized as follows: The system model is described in Section II, and the SSE functions are proposed in Section III. Then, in Section IV, the simulation model is described, before the performance evaluation is presented in Section V. Section VI concludes the paper. Finally, Appendix A describes how we enhance the NS-2 simulator with respect to the spectrum sensor design and implementation.

II. System Model

A. IEEE 802.22 Network Model

We consider an opportunistic cognitive radio system based on the IEEE 802.22 standard. It is limited to one Base Station (BS) and N mobile Opportunistic Users (OUs), as illustrated in Fig. 1. It is assumed that M channels with frequencies $F_1, \cdots, F_M$ are available for use by the IEEE 802.22 system after consulting the spectrum database. Furthermore, there are M unregistered WM Tx-Rx pairs, so that there is exactly one pair appearing in each of the M available channels. A personal computer (PC) is connected via Ethernet to the BS. The PC establishes links to the OUs and runs the traffic models.

The WM activity will be detected by sensing techniques only, and with no support from a beacon protocol, like IEEE 802.22.1. Finally, the IEEE 802.22 self-coexistence protocol [8] is not used, since a single cell is considered.

B. Traffic Model

1) IEEE 802.22 Traffic Model: The traffic is modeled as constant bit rate (CBR) in the IEEE 802.22 system. CBR runs over UDP. Different traffic rates are simulated by constantly transmitting UDP packets of size 1500 Bytes to each OU. The CBR traffic uses the best effort (BE) QoS traffic profile in IEEE 802.22, which provides fairness between the OUs.

2) Wireless Microphone Traffic Model: A WM pair in the simulator are two WMs communicating with a typical distance of 100 m. When a WM is turned on and becomes active, its traffic pattern is characterized by a 100% duty cycle (irrespective whether someone is speaking to the microphone or not) until the WM is turned off again and disappears. Since WMs typically are present in venues such as churches, schools and concert halls, and since WMs thus often appear on a channel at specific times (e.g. each evening), we model their appearance pattern according to an ON-OFF model. It is assumed that all WMs generate new connections according to the negative exponential distribution for the average inter-arrival time $1/\lambda_w$ and average on time $1/\mu_w$ which is common in wireless communications [16]. A related study on sensing in IEEE 802.22 [17] also uses an ON-OFF model.

III. Spectrum Selection Functions

Three different SSE functions are proposed as described below. These will not replace the spectrum management functionality specified in the IEEE 802.22 standard, but will be complementary and coexist to enhance performance by considering statistics calculated over longer time periods. The first function *SSE-Power* is a basic algorithm used to benchmark the three proposed SSE functions.

A. SSE-Power (Reference Function)

The *SSE-Power* function selects the channel where the spectrum sensor has detected the lowest total signal power from WMs. No historical measurements are used.

The *SSE-Power* function uses sensing results $\{r_{i,j}\}$ from OU_i on channel j, and selects the optimal channel ch_{Opt}^{Power} based on the following criteria:

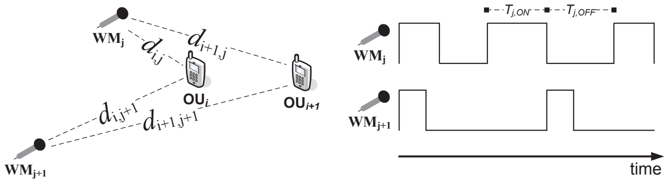
$$ch_{Opt}^{Power} = \min_j \{\max_i \{r_{i,j}\}\}, \tag{1}$$
$$\text{subject to: } r_{i,j} < \eta, j \in [0, M], i \in [0, N],$$

where N is the total number of OUs connected to the BS, M the total number of channels to be sensed and η the sensing detection threshold (–107 dBm over 200 kHz in the simulator).

B. SSE-Distance

The *SSE-Distance* function enhances QoS when the cognitive radio terminals are mobile. It is motivated by the fact that primary users, such as WMs, are located and often appear at the same geographical locations. The goal is to predict the WM location on each channel and select the channel with farthest distance from the BS and OUs to the WM.

To predict the location of a WM on a channel, *SSE-Distance* uses trilateration. It is assumed that the BS and OUs know their geo-location and that WM transmit power is known. First, *SSE-Distance* uses historical measurements from the BS and OUs to predict the distance to the WM on each channel, using the Okumura-Hata propagation model [18]. Then, *SSE-Distance* selects the shortest distances to the WM. These distances and the geo-location coordinates of the measuring BS and OUs are then used to predict the WM location using trilateration. Having predicted the WM location on all channels, *SSE-Distance* is able to find the current shortest distance from the BS and OUs to the WM on each channel. Finally, the channel with current farthest distance from the



(a) Illustration of *SSE-Dist* policy (b) Illustration of *SSE-OnOff* policy
Fig. 2. Illustration of SSE functions.

BS and OUs to the nearest WM is then selected for use. *SSE-Distance* as well as *SSE-OnOff* and *SSE-Hybrid* are proactive in that the SSE function runs automatically if no WM activity is detected within 5 seconds after the SSE function was run.

Mathematically, *SSE-Distance* finds the distances $\{d_{i,j}\}$ from the BS and each OU_i to the closest WM on each channel j based on sensing measurements, and then selects the optimal channel $ch_{Opt}^{Distance}$ based on the following criteria:

$$ch_{Opt}^{Distance} = \max_{j}\{\min_{i}\{d_{i,j}\}\}, \tag{2}$$
$$\text{subject to: } r_{i,j} < \eta, j \in [0, M], i \in [0, N].$$

In the example scenario for *SSE-Distance* illustrated in Fig. 2(a), $d_{i,j}$ and $d_{i,j+1}$ are the shortest distances on channel j and $j+1$ respectively. Since $d_{i,j}$ is shorter than $d_{i,j+1}$, channel $j+1$ will be selected.

C. SSE-OnOff

The *SSE-OnOff* function aims to enhance QoS and performance of the mobile OUs in scenarios where the WM density and activity level is high. This function is motivated by the fact that WMs often use the channel at specific time intervals. *SSE-OnOff* uses sensing to predict the probability that a channel will not be occupied by a WM. To do this, sensing measurements from the BS and OUs are used to calculate the mean values for the channel ON (busy) and OFF (idle) periods for the WM for each channel j, denoted $\mathbb{E}[T_{j,ON}]$ and $\mathbb{E}[T_{j,OFF}]$ respectively. Note that other approximations than taking the mean could be used [13], [14], [19]. These statistics are then used to select the optimal channel ch_{Opt}^{OnOff} based on the following criteria:

$$ch_{Opt}^{OnOff} = \max_{j} \frac{\mathbb{E}[T_{j,OFF}]}{\mathbb{E}[T_{j,OFF}] + \mathbb{E}[T_{j,ON}]}, \tag{3}$$
$$\text{subject to: } r_{i,j} < \eta, j \in [0, M].$$

The sensing sampling rate for determining $T_{j,ON}$ and $T_{j,OFF}$ in the operating channel equals the coarse sensing period $T_p = 2\,\text{s}$ (see Section IV-C2). In backup channels, the BS and OUs sense during idle periods no longer than T_p.

In the example scenario for *SSE-OnOff* illustrated in Fig. 2(b), since WM_j has higher activity pattern than WM_{j+1}, channel $j+1$ will be selected.

D. SSE-Hybrid

SSE-Hybrid combines *SSE-Distance* and *SSE-OnOff* to use the optimal function depending on spectrum usage statistics. The goal is to enhance QoS and performance both when the OUs are mobile and the density of WMs and/or OUs is high.

We want to use *SSE-Distance* when the distance $d_{i,j}$ between OU_i and WM_j on channel j is high, and *SSE-OnOff* when $d_{i,j}$ is low for all backup channels. A distance threshold d_{th} is defined as criteria for deciding which SSE function to use during system run-time. Different distance thresholds are used for the BS and OUs referred to as d_{th}^{bs} and d_{th}^{ou}. The *SSE-Hybrid* function is configured to select the optimal channel ch_{Opt}^{Hybrid} based on the following criteria:

$$ch_{Opt}^{Hybrid} = \begin{cases} ch_{Opt}^{Distance}, & d_{i,j} > d_{th}^{ou}, d_{bs,j} > d_{th}^{bs} \\ ch_{Opt}^{OnOff}, & \text{else} \end{cases} \tag{4}$$
$$\text{subject to: } r_{i,j} < \eta, j \in [0, M], i \in [0, N].$$

Our strategy for selecting the distance threshold is to have it equal to the WM detection range:

$$\eta > TX_{wm} - PL(d_{th}). \tag{5}$$

where TX_{wm} dBm is the WM transmit power and $PL(d_{th})$ is the path loss found by using the Okumura-Hata model [18]. We can then express d_{th} in kilometers from (5) as:

$$d_{th} > 10^{\frac{TX_{wm} - \eta - 69.55 - 26.16 \cdot log_{10}(f) + 13.82 \cdot log_{10}(h_b) + C_H}{44.9 - 6.55 \cdot log_{10}(h_b)}}, \tag{6}$$

where f is the frequency in MHz, h_b the BS height in meters and C_H a correction factor for user terminal height.

IV. IEEE 802.22 Simulation Model

In this section we recapitulate parts of description of the simulator presented first in [4]–[7]. An extensive implementation of IEEE 802.16 in NS-2 [20] is adapted to the IEEE 802.22 standard. The main parameters in our IEEE 802.22 NS-2 simulation model [4]–[7], which uses the 6 MHz profile, are given in Table I. Channel bonding [9] of scattered available channels is not considered, therefore only one available UHF channel is used by the IEEE 802.22 system. A WM occupies only one channel.

A. Medium Access Control and OFDMA Implementation

IEEE 802.22 uses Time Division Duplex (TDD) and the DL:UL (downlink:uplink) ratio is set to 2:1 in the simulator. There are totally 26 symbols, each of 373.33 μs duration. Both the DL and UL subframes have 60 subchannels, each consisting of 28 subcarriers. Guard bands are considered at upper and lower ends of the channel with a total of 368 guard and null subcarriers. For the subcarrier allocation strategy, partially usage of subcarriers (PUSC) allocation is used. The MAC layer uses linear scheduling to allocate OFDMA slots to traffic from the upper layers in both the DL and UL subframes. An OFDMA slot can be characterized as a $\{$subchannel, symbol$\}$-pair in the frequency and time domain. Vertical striping is used for both DL and UL subframes in the simulator, which means that OFDMA slots are allocated first in terms of frequency and then in terms of time. The IEEE 802.22 network can operate on any vacant TV channel not used by the primary user.

TABLE I
NS-2 IMPLEMENTATION OF THE IEEE 802.22 STANDARD [1] (REFER TO A SIMILAR TABLE IN [4]–[7])

Parameter	IEEE 802.22 NS-2
Bandwidth	6 MHz
FFT Size	2048
Frequency/Channels	54–698 MHz
Frame size	10 ms
Duplexing method	TDD
Tx/Rx Transit Gap (TTG)	81.8 μs
Rx/Tx Transit Gap (RTG)	209.9 μs
Modulation types	QPSK, {16,64}-QAM
Coding rates	1/2, 2/3, 3/4
Max EIRP	BS: 36 dBm, OU: 20 dBm
Assumed noise figure	BS/OU: 4 dB
QoS classes	UGS, BE
Cyclic prefix mode	1/4
OFDM mapping	vertical
Error protection	Automatic Repeat Request (ARQ)
Subcarrier. spacing	3.348 kHz
Useful symbol length	298.7 μs
Guard time	37.34 μs
Symbol duration	373.3 μs
Sampling frequency	6.857 MHz
Sampling period	0.299 ms
Symbols per frame	26
Used subcarriers	1680
Guard and null subcarriers	368
Pilot subcarriers	DL/UL: 240
Data subcarriers	DL/UL: 1440
Subcarriers/subchannel	DL/UL: 24
Subchannels	DL/UL: 60
Pilot location	Distributed
Subcarrier allocation	PUSC
Sensing strategy	two-stage sensing
Coarse sensing duration	1 ms
Coarse sensing interval	2 sec
Fine sensing duration	30 ms
Fine sensing interval	∞ (event based)
Cooperative sensing	”OR” rule
WM detection threshold	-107 dBm

B. Physical Layer and Propagation Model

The propagation model used in the simulator is the Okumura-Hata [18] path loss model, configured for light urban scenarios. Furthermore, the Okumura-Hata model is combined with a Clarke-Gans implementation of Rayleigh fading. The Vehicular A ITU power delay spread model is used which is suited for the considered scenario. The BS and OU EIRP is set to 36 dBm and 20 dBm respectively.

Interference modeling is done at the subcarrier level by capturing packets from all IEEE 802.22 nodes and WMs. When the received signal to interference plus noise ratio (SINR) on each subcarrier is calculated for each packet, a decision is made to further process or drop the packet. Channel errors are considered in the simulations and ARQ is implemented as specified in the IEEE 802.22 standard. If the block error rate (BLER) extracted from the SINR, modulation and coding rate and block size, is above a threshold set to 4%, the simulator emulates that the erroneous bits are corrected[1].

C. Spectrum Manager and Spectrum Sensing Implementation

1) Spectrum Manager: The spectrum manager implemented in the BS controls the spectrum sensing and geo-location functions. It decides which channel to use and specifies the set of channel lists, i.e. the backup, candidate and protected channel lists. In our simulator, the backup channels are subject for selection by the SSE functions. In the OU, the spectrum automaton is a lightweight version of the spectrum manager. It is mainly responsible for reporting to the BS and for sensing when not connected to the BS. Dynamic transmit power control is not implemented. Hence, the IEEE 802.22 switches to a new channel if a WM is detected on that channel.

2) Spectrum Sensing Implementation: The spectrum sensing function can first be classified into in-band sensing, which senses the operating channel, and out-of-band sensing, which senses activity on other channels that potentially can be used. For in-band sensing the two-stage spectrum sensing approach, as specified by the standard, is implemented as the default sensing strategy in the simulator. At the coarse sensing stage (first stage) a simple energy detection is used for frequent and short sensing periods $T_c = 1$ ms during allocated time periods at the end of the uplink OFDMA subframe. Sensing occurs every n_c OFDMA frame. If coarse sensing detects a WM signal, it switches to the fine sensing stage (second stage)[2], which uses a more detailed WM detection process for a longer period $T_s = 30$ ms. An energy detector is also used for fine sensing in the simulator. If a WM signal is detected by fine sensing then the operating channel is switched to one of the backup channels. A pre-defined interval between fine sensing periods T_I is set if the event based strategy is used.

In the simulation, probability of detection P_D and false alarm P_{FA} are set separately for coarse and fine sensing. P_{FA} is set to a given value, while P_D is defined by a function of P_{FA} as detailed for the energy detector design described in Appendix A. The effect of P_D and P_{FA} will mostly be considered for coarse sensing which is more unreliable than fine sensing. Fine sensing, which uses more advanced sensing techniques is assumed to be very accurate and is modeled to be ideal, hence P_D and P_{FA} are therefore set to one and zero, respectively. Further, cooperative sensing with the OR rule is implemented for all sensing stages. This is mandatory in the US as specified by the IEEE 802.22 standard [1, Sec. 8.6.1.3].

In this study we implement and evaluate three sensing strategies for in-band sensing in IEEE 802.22:

1) Two-stage spectrum sensing [1]: with coarse sensing every $n_c = 200$ OFDMA frame;
2) Two-stage consecutive spectrum sensing [21]: same as above, but $\delta = 2$ consecutive coarse detections are needed before fine sensing is triggered;
3) Single-stage spectrum sensing: fine sensing only with $T_I = 2$ sec (i.e. interval between fine sensing stages).

Finally, out-of-band sensing is performed on all channels

[1]Please refer to [20] for a detailed description of the OFDMA physical layer implementation and interference modeling. Note that the system profiles, propagation model and operating frequency range are reimplemented to fit the UHF bands, IEEE 802.22 and light urban scenario [4]–[7].

[2]Note that in our simulation model coarse sensing detection triggers fine sensing immediately as in [21], but differs from [8], [9] where coarse sensing results are used to decide if the next scheduled fine sensing stage should be cancelled. In [17], either coarse or fine sensing is used to minimize sensing overhead while meeting detection requirements.

during quiet periods allocated for the fine sensing periods and during idle periods when BS or OU not transmits or receives.

D. Wireless Microphone Implementation

A typical analog WM in the TV bands uses a narrow 200 kHz bandwidth, which corresponds to 68 active subcarriers in the NS-2 simulator. Since an analog WM most of the time focuses its transmit power on a narrow part of the 200 kHz bandwidth, we assume that the WM on average uses half the bandwidth. Hence, the WM transmit power of 50 mW will be distributed over the 34 subcarriers in the NS-2 simulator.

E. System Performance Metrics

The metrics used to evaluate the IEEE 802.22 performance in the studied scenario are:

1) Throughput: measured at the transport layer for the application used. Note that this will not reflects the physical layer throughput since management frames at the MAC layer and general network layer overhead not is counted.
2) Packet Loss: measured at the network layer as the percentage of packets transmitted but not received.
3) Delay: measured at the application layer as the time from the packet is transmitted until it is received. Includes delay in all TCP/IP protocol layers.
4) SINR: Signal-to-Interference plus Noise Ratio resulting from Gaussian noise and interference from WMs.
5) OU outage: is the percentage of packages that experience C/I values below the required SINR threshold.

Furthermore, to assess the impact on the WM performance we use the following metrics:

1) WM C/I: is the carrier to interference ratio measured at the WM, which is considered as the metric that best describes the performance of the analog WM. The only interference is from the IEEE 802.22 system.
2) WM outage: is the percentage of time the WM experience C/I values below the required C/I level, with typical required C/I of 25 dB [22].

The metrics will mostly be presented as one average value for all OUs and WMs.

V. Performance Evaluation

A. Scenario Description

The scenario considered is a mobile cellular network in a light urban area that can be used to extend capacity in traditional cellular networks. Each of the mobile OUs move following a random waypoint model with a random speed between 1 and 20 m/s. Their initial location is randomly selected within the BS cell radius of 1.2 km. The basic parameters used in the simulation scenario are given in Table II.

The number of available TV white space channels after consulting the geo-location database is assumed to be $M = 4$. Four unregistered WM pairs will appear on these channels, each one appearing separately on one of the 4 channels. Their location is randomly selected within the area of 1.4 km radius from the BS. Their average inter-arrival and on time will be selected randomly following a uniform distribution $1/\lambda_w = 20 \pm 10$ and $1/\mu_w = 5 \pm 2.5$ seconds respectively (i.e in the intervals $[10, 30]$ and $[2.5, 7.5]$). Note that during simulation, both the WM inter-arrival and on times vary according to the negative exponential distribution. For *SSE-Hybrid*, the values for the distances thresholds in (6) for ch^{Hybrid}_{Opt} given in (4) are $d^{bs}_{th} > 0.885$ and $d^{ou}_{th} > 0.436$ km.

TABLE II
PARAMETERS USED IN THE SIMULATION SCENARIO

Parameter	Value
IEEE 802.22 BS height	15 m
IEEE 802.22 OU height	1.5 m
IEEE 802.22 BS cell radius	1.2 km
IEEE 802.22 OU traffic load	200 kbit/s
IEEE 802.22 OU speed	$1 \dots 20$ m/s (random), random waypoint
#IEEE 802.22 OU (N)	$4 \dots 16$
Modulation and Coding	16-QAM 1/2
WM height	1.5 m
WM EIRP	0.05 W (17 dBm)
WM bandwidth	200 kHz
WM inter-arrival time ($1/\lambda_w$)	20 ± 10 (uniform distribution)
WM on time ($1/\mu_w$)	5 ± 2.5 (uniform distribution)
WM pairs distance	100 m
#WM pairs	4
Available channels (M)	4
Frequency bands	600 MHz (channels with center frequencies 605, 611, 617, 623)
Traffic direction	Downlink (DL)

About 80 simulations are run for each of the results presented, each with a duration of 550 s. The results are averaged. A warm up time of 50 s is used to ensure a stable point of network operation. Considering that in NS-2 all nodes receive packets from all other nodes, irrespective of actual frequency used, and that the nodes processes the packet fully or partially, each single simulation takes about 1-2 hours depending on the number of OUs on modern computers (RedHat Enterprise Linux v5.8, 64-bit, 8 CPUs, 16 GB, 2.3 Hz).

B. Performance without presence of WMs

Fig. 3 presents the throughput when there are no WMs present for the sensing configurations; two-stage sensing with $\{n_c$=200, δ=1$\}$, $\{n_c$=2, δ=1$\}$ and $\{n_c$=10, δ=1$\}$, two-stage consecutive sensing with $\{n_c$=2, δ=2$\}$, and fine sensing with $\{n_c$=∞, T_I=2$\}$. Recall that n_c is the number of OFDMA frames between coarse sensing stages, δ is the number of consecutive detections needed before fine sensing is triggered and T_I is the interval between fine sensing stages in seconds.

It is observed that all sensing configurations achieve similar performance for 4 to 10 OUs. For more than 10 OUs the throughput degrades for $\{n_c$=2, δ=1$\}$ since the higher number of OUs causes more false alarms. This results in more fine sensing stages, which give overhead. This is also observed for $\{n_c$=2, δ=10$\}$ for more than 12 OUs. The consecutive sensing strategy $\{n_c$=2, δ=2$\}$ becomes similar to $\{n_c$=200, δ=1$\}$ since the number of fine sensing stages started by false alarms is reduced, where only a 6 Kbit/s lower throughput is observed for 16 OUs. The fine sensing configuration $\{n_c$=∞, T_I=2$\}$ achieves lower throughput for 16 OUs since more time is used for fine sensing (30 ms for each 2 seconds).

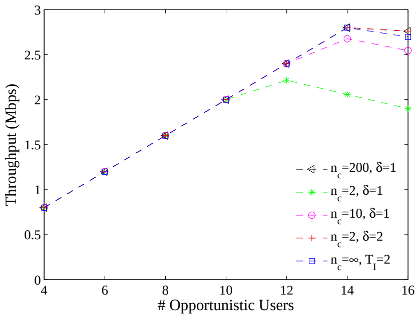


Fig. 3. Throughput for different sensing configurations with no WMs present.

C. Evaluation of SSE Functions for Increasing Number of Opportunistic Users

Simulation results for increasing number of OUs for *SSE-Power*, *SSE-Distance*, *SSE-OnOff* and *SSE-Hybrid* are presented in Fig. 4, in addition to the case without presence of WMs for $\{n_c$=200, δ=1$\}$, referred to as “No WMs”.

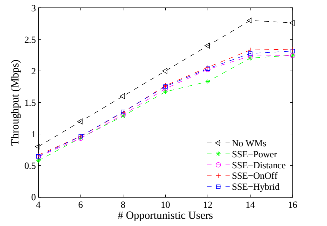
From the average system throughput for all OUs given in Fig. 4(a) it is first observed that the three proposed SSE functions achieve higher throughput than *SSE-Power*. (95% confidence intervals, not included in the plots due to visibility, are in the range 0.04 to 0.14 for *SSE-Power* and 0.02 to 0.08 for the proposed SSE functions.). It is also seen that *SSE-OnOff* always achieves highest throughput. This is because when the WM activity is quite high as in the considered scenario, *SSE-OnOff* will more often select the channel that stays idle for the longest period. Hence, the number of channel switches and the average interference is reduced (see average WM C/I in Fig. 4(e)). Average packet loss given in Fig. 4(b) is generally highest for *SSE-Power* and lowest for *SSE-OnOff*, which complies with the observation in Fig. 4(a).

SSE-Distance achieves higher throughput than *SSE-Power*. Since *SSE-Power* selects channel without knowledge about where the WM might appear, which might be close to the OU, both the OU and WM will often experience harmful interference. It was observed especially for *SSE-Power* that this resulted in the OU losing synchronization with the BS. This reduces throughput dramatically (and explains the dip in throughput for 12 OUs). This was also observed for the other SSE functions, but less frequently.

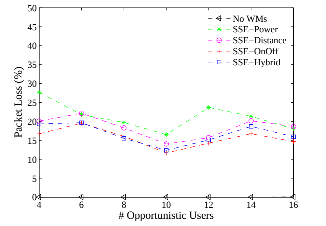
SSE-Hybrid does not achieve maximum throughput all the time as desired, which means that the optimal SSE function not is selected all the time in this scenario. Hence, other threshold values in (4) or another selection criteria should be used.

Average delay given in Fig. 4(c) is around 18 milliseconds when the number of OUs and traffic load is low, and increases as load increases. It can be seen that packet loss increases dramatically when the IEEE 802.22 OFDMA frame is full.

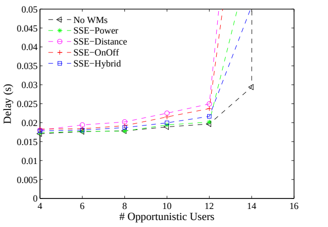
Average SINR measured at the OUs given in Fig. 4(d) show a notable increase in SINR for 14 OUs. It also observed that interference from OUs to WMs increases at this point for *SSE-Distance*, *SSE-OnOff* and *SSE-Hybrid* (see average WM C/I in Fig. 4(e)). The reason for the increase in SINR at this point has not yet been identified and is left for further work.



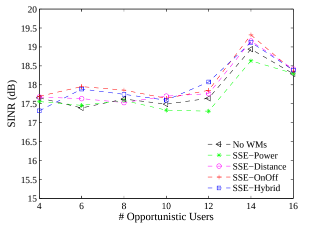
(a) Average IEEE 802.22 Throughput



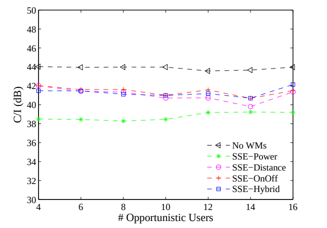
(b) Average Packet Loss for OU



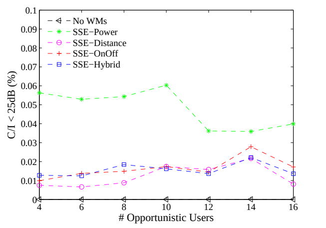
(c) Average Delay for OU



(d) Average SINR for OU



(e) Average C/I for WM



(f) Average percentage of time WM C/I<25 dB

Fig. 4. Performance for the SSE functions for increasing number of OUs.

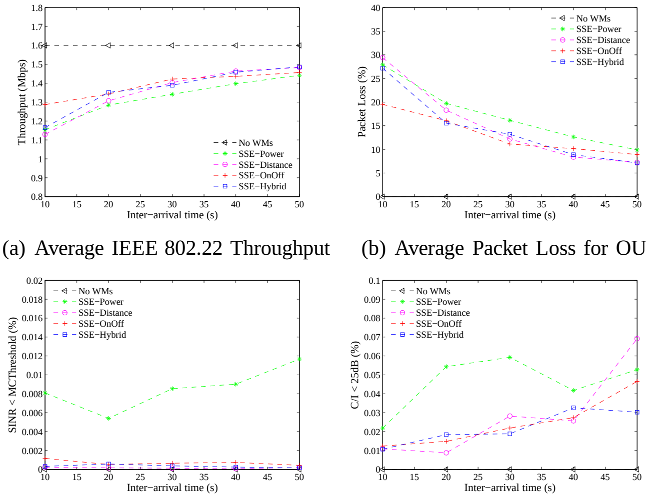
Average experienced C/I for the WMs given in Fig. 4(e) is quite high in general. Thus, interference does not impact much on WM performance. It is seen that *SSE-Power* causes most interference to the WMs, which is because it selects channel without historical knowledge about where and how often the WMs appear. One observation is that interference to the WMs seems to increase slightly for *SSE-Distance* when the number of OUs increases, which is because the average distance to the nearest WM decreases as the number of OUs increases.

A better measure of harmful interference is the percentage of time the WM experience C/I below 25 dB given in Fig. 4(f), which also is highest for *SSE-Power*. Impact on the WM is found to be lower for the three proposed SSE functions, and is observed to occur only for a short period when the WM appears between sensing periods. Interestingly, *SSE-OnOff* generally gives more harmful interference than *SSE-Distance* despite the higher average interference for *SSE-Distance* in Fig. 4(e). This is because the OUs select channel without knowledge about WM location. Hence, harmful interference occurs more often since the WM appears close to an OU.

D. Evaluation of SSE Functions for Various WM Activity

The simulation results for increasing WM inter-arrival time (i.e. for lower WM activity) when there are 8 OUs for the different SSE functions are presented in Fig. 5.

From the average throughput and packet loss for all OUs in Fig. 5(a) and 5(b), it is seen that *SSE-OnOff* achieves best performance for high WM activity with inter-arrival time 10,



(a) Average IEEE 802.22 Throughput

(b) Average Packet Loss for OU

(c) Average percentage of SINR < Modulation and coding threshold

(d) Average percentage of time WM C/I<25 dB

Fig. 5. Performance of the SSE functions for various WM activity levels.

20 and 30 s and that *SSE-Distance* achieves best performance as the WM activity reduces. It is evident that the effect of *SSE-OnOff* reduces as WM activity reduces. These findings support the hypotheses H.1 and H.2 stated in Section I. However, *SSE-Hybrid* does not achieve highest performance all the time as proposed in H.3. This means that the threshold values in (4) not are optimal or that a new selection criteria must be used.

Average percentage of received packets that obtain SINR value less than the modulation and coding rate threshold given in Fig. 5(c) is highest for *SSE-Power*, which often selects channel without knowledge of how often or where WMs are located. *SSE-Power* generally causes more harmful interference to the WMs as illustrated in Fig. 5(d). It can also be seen that harmful interference generally increases as WM activity reduces. Similarly, it was also found that average WM C/I (not shown here) reduces as WM activity reduces, which is because the probability that the IEEE 802.22 system has started using a channel between the WM inter-arrival times increases as the WM activity reduces. Another reason for this observation is that the number of useful statistical data samples (sensor measurements) for use by the SSE functions during the simulation time reduces as WM activity reduces.

VI. Conclusions

Three SSE functions that utilize sensing results to provide long-term spectrum usage statistics were evaluated through system level simulations, using a detailed implementation of the IEEE 802.22 standard in NS-2; *SSE-Distance* that aims to improve performance when the cognitive radio users are mobile by selecting the channel with longest distance between IEEE 802.22 devices and WM; *SSE-OnOff* that aims to improve performance when WM activity is high by selecting the channel with the highest probability of being available, and *SSE-Hybrid* that combines the former two to use the optimal SSE function depending on spectrum usage statistics. It was found that these SSE functions can complement existing spectrum management functions to enhance performance in the IEEE 802.22 network. Harmful interference was reduced for both the IEEE 802.22 network and the WM. This resulted in a more stable network with higher system throughput. *SSE-OnOff* performed best when the WM activity was high and *SSE-Distance* performed best when the WM activity was reduced. We did not always obtain optimal performance for the proposed *SSE-Hybrid* function. Better understanding and optimization of *SSE-Hybrid* is considered for future work.

Appendix A
Energy Detector Design

The energy detector [1, Section C.1.1] is simple in that it determines if a signal is present or not on a channel by comparing the sensed signal energy with a given threshold. To detect whether the signal is present or not, two hypotheses are set up for the sampled signal $y(n)$ at the energy detector:

$$H_0 : y(n) = w(n), \tag{7}$$
$$H_1 : y(n) = x(n) + w(n), \tag{8}$$

where $x(n)$ is the received signal samples and $w(n)$ is the noise samples, which respectively have power P_S and P_N.

The signal energy is measured during a finite time interval and compared to a threshold γ. The test statistic of the energy detector is:

$$\tau = \sum_{n=1}^{M} |y(n)|^2. \tag{9}$$

Since we have a large number of samples M in the vector y, the test statistic can be approximated as a Gaussian random variable by the central limit theorem:

$$\tau \sim N\left(P_s + P_N, \frac{(P_s + P_N)^2}{M}\right). \tag{10}$$

The detector threshold can then be found based on the required false alarm probability P_{FA}:

$$\gamma = P_N\left[1 + \frac{Q^{-1}(P_{FA})}{\sqrt{M}}\right]. \tag{11}$$

The probability of detection in an AWGN channel is then:

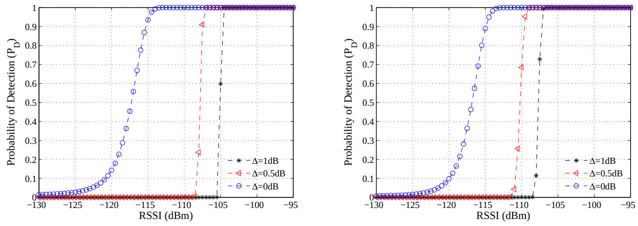
$$\begin{aligned} P_D &= P\{\tau > \gamma | H_1\} \\ &= 1 - Q\left(\frac{\sqrt{M}}{P_S + P_N}(P_S + P_N - \gamma)\right). \end{aligned} \tag{12}$$

In the simulator we calculate the probability of missed detection when a WM signal is sensed, which is given by:

$$P_{MD} = 1 - P_D = Q\left(\frac{\sqrt{M}}{P_S + P_N}(P_S + P_N - \gamma)\right). \tag{13}$$

The energy detector works well when the noise power P_N is known. However, it is difficult to estimate the noise power exactly. Hence, we assume that the noise power has an uncertainty of $\pm\Delta$ dB [17]. Taking this into account, P_N is:

$$P_N = 10 \cdot \log_{10}(kTB) + NF \pm \Delta, \tag{14}$$



(a) $P_{FA} = 0.01$, $M = 6000$, $T_c =$ 1 ms, sensing BW=6 MHz

(b) $P_{FA} = 0.005$, $M = 1500$, $T_c =$ 0.5 ms, sensing BW=3 MHz

Fig. 6. Probability of detection for noise uncertainty $\Delta = 0$, 0.5 and 1 dB as function of RSSI, for noise figure 4 dB and detection threshold –107 dBm.

where k is the Boltzmann constant, $T = 300$ Kelvin is the temperature, $B = 6$ MHz is the bandwidth and $NF = 4$ is the receiver noise figure.

For a given detector threshold γ, the P_{FA} is:

$$P_{FA} = P\{\tau > \gamma | H_0\} = 1 - Q\left(\frac{\sqrt{M}}{P_N}(P_N - \gamma)\right). \quad (15)$$

Now, the detection threshold γ can be calculated for a considered $P_{FA} = 0.01$ by using (11) with P_N as in (14) with noise uncertainty $\Delta = 0$ dB. Furthermore, the calculated detection threshold γ is used to find the worst case P_D and P_{MD}. Sensing time is set to 1 ms, hence we will have $M = 6$ MHz $\cdot$ 1 ms $= 6000$ samples. The sensing threshold for a WM is –107 dBm (averaged over 200 kHz) [1]. The resulting P_D for $\Delta = 0, 0.5$ and 1 dB are given in Fig. 6(a) for different received signal strengths (RSSI). It can be seen that the minimum signal that can be detected for $\Delta = 0.5$ and 1 dB are -108.9 dBm and -105.7 dBm respectively. This indicates that the energy detector with noise uncertainty $\Delta = 1$ will not be able to detect the WM at -107 dBm.

In a realistic scenario, it will be reasonable to consider $\Delta = 1$ dB. Hence, we design our sensor to divide the sensing stage into two sub-sensing stages each sensing 3 MHz for 0.5 ms. This will reduce the noise floor with 3 dB. However, the number of sensing samples reduces to $M = 3$ MHz $\cdot$ 0.5 ms $= 1500$. False alarm for each of the $N = 2$ sub-sensing stages can be found by using $P_{FA} = 1 - (1 - P_{FA}^{sub})^N$ that gives $P_{FA}^{sub} = 0.005$ (can also be found with Eq. (15)). A potential issue with this sensor design is that a WM can appear on the border between the two 3 MHz bands for the two sub-sensing stages. However, we consider this a minor issue since the sensor could be designed with a small overlapping area in the sensed bandwidths for the two sub-sensing stages. The resulting P_D for $\Delta = 0$, 0.5 and 1 dB is given in Fig. 6(b). It is found that the power wall is –108.8 dBm for $\Delta = 1$ dB, and that $P_D = 0.993$ for $RSSI = -107$ dBm.

For the simulation model, we set $P_{FA} = 0.01$ or more specifically $P_{FA}^{sub} = 0.005$ for each of the two sub-sensing stages each over 3 MHz. Missed detection is randomly selected with a probability P_{MD} based on a table lookup for (13).

REFERENCES

[1] *IEEE Standard for Information Technology–Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)–Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands*, IEEE Std 802.22-2011, 2011.

[2] C. R. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. J. Shellhammer, and W. Caldwell, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE Commun. Mag.*, pp. 130–138, Jan. 2009.

[3] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl, "Senseless: A database-driven white spaces network," *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, pp. 189–203, feb. 2012.

[4] P. Grønsund, P. Pawełczak, J. Park, and D. Čabrić, "System level performance of IEEE 802.22 with sensing-based detection of wireless microphones," submitted to IEEE Commun. Mag. 2012.

[5] J. Park, P. Pawełczak, P. Grønsund, and D. Čabrić, "Analysis framework for opportunistic spectrum OFDMA and its application to IEEE 802.22 standard," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2271–2293, Jun. 2012.

[6] P. Grønsund, P. Pawełczak, J. Park, and D. Čabrić, "Sensing of wireless microphones in IEEE 802.22: A system level performance evaluation," accepted for publication to IEEE ICC 2013.

[7] P. Pawełczak, J. Park, P. Grønsund, and D. Čabrić, "System level analysis of ofdma -based networks in tv white spaces: IEEE 802.22 case study," in *TV White Space Spectrum Technologies: Regulations, Standards and Applications*, R. A. Saeed and S. J. Shellhammer, Eds. CRC Press, 2011, ch. 8, pp. 209–238.

[8] C. Cordeiro, K. Challapali, and M. Ghosh, "Cognitive PHY and MAC layers for dynamic spectrum access and sharing of TV bands," in *Proc. ACM Workshop TAPAS*, New York, NY, USA, Aug. 5, 2006.

[9] K. Challapali, C. Cordeiro, and D. Birru, "Evolution of spectrum-agile cognitive radios: first wireless internet standard and beyond," in *Proc. ACM Workshop WICON*, New York, NY, USA, Aug. 2–5, 2006.

[10] P. A. Kumar Acharya, S. Singh, and H. Zheng, "Reliable open spectrum communications through proactive spectrum access," in *Proc. ACM Workshop TAPAS*, New York, NY, USA, Aug. 5, 2006.

[11] L. Yang, L. Cao, and H. Zheng, "Proactive channel access in dynamic spectrum networks," *Physical Communication*, vol. 1, no. 2, pp. 103–111, Jun. 2008.

[12] M. Höyhtyä, S. Pollin, and A. Mammela, "Performance improvement with predictive channel selection for cognitive radios," in *Proc. IEEE Workshop CogART*, Feb. 14, 2008.

[13] K. Arshad and K. Moessner, "Statistical models of spectrum opportunities for cognitive radio," in *Proc. IEEE PIMRC*, sept. 2011.

[14] S. Geirhofer, L. Tong, and B. Sadler, "Cognitive radios for dynamic spectrum access - dynamic spectrum access in the time domain: Modeling and exploiting white space," *IEEE Commun. Mag.*, vol. 45, no. 5, pp. 66 –72, may 2007.

[15] C.-H. Jiang and R.-M. Weng, "Cognitive engine with dynamic priority resource allocation for wireless networks," *Wireless Personal Communications*, vol. 63, no. 1, pp. 31–43, Mar. 2012.

[16] M. Wellens, J. Riihijärvi, and P. Mähönen, "Empirical time and frequency domain models of spectrum use," *Elsevier Physical Communication Journal*, vol. 2, no. 1–2, pp. 10–32, Mar.–Jun. 2009.

[17] H. Kim and K. Shin, "In-band spectrum sensing in IEEE 802.22 WRANs for incumbent protection," *IEEE Trans. Mobile Comput.*, vol. 9, no. 12, pp. 1766 –1779, dec. 2010.

[18] Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda, "Fieldstrength and its variability in VHF and UHF land mobile radio service," *Review of the Electrical Communications Laboratory*, vol. 16, no. 9-10, pp. 825–873, sept. 1968.

[19] M. Lopez-Benitez and F. Casadevall, "Empirical time-dimension model of spectrum use based on a discrete-time markov chain with deterministic and stochastic duty cycle models," *IEEE Trans. Veh. Technol.*, vol. 60, no. 6, pp. 2519–2533, july 2011.

[20] N. Golmie et. al. (2009) WiMAX forum system level simulator NS-2 MAC+PHY add-on for WiMAX (IEEE 802.16). [Online]. Available: http://code.google.com/p/ns2-wimax-awg/

[21] W. S. Jeon, D. G. Jeong, J. A. Han, G. Ko, and M. S. Song, "An efficient quiet period management scheme for cognitive radio systems," *IEEE Trans. Wireless Commun.*, vol. 7, no. 2, pp. 505–509, Feb. 2008.

[22] "Digital dividend: Cognitive access, statement on licence-exempting cognitive devices using interleaved spectrum," Ofcom, Tech. Rep., Jul. 2009.