Social-Aware Energy Harvesting Device to Device Communications in 5G Networks

Li Jiang, Hui Tian, Zi Xing, Kun Wang, Ke Zhang, Sabita Maharjan, Stein Gjessing, and Yan Zhang

Abstract—With ever-increasing demands for local area services in the fifth generation (5G) cellular networks, solutions are necessary to deliver local area data in both a spectrum- and an energy-efficient manner. In this paper we propose a new cellular communication architecture which integrates energy harvesting technologies and social networking characteristics into device-to-device (D2D) communications for local data dissemination. The proposed architecture includes three domains: the physical domain, the energy domain and the social domain. Specifically, in the physical domain, D2D communications enable two nearby users to communicate with each other directly. In the energy domain, devices harvest energy from renewable energy sources. In the social domain, D2D users form social networks exhibiting stable social structures and relations. Then we mainly focus on the efficient local data dissemination issues in the proposed architecture and propose two social-aware energy harvesting D2D communication schemes (a device relaying and a device multicast). Illustrative results demonstrate significant spectrum and energy efficiency enhancement for local data dissemination in 5G cellular networks.

I. INTRODUCTION

With the emergence of the Internet of Things (IoT) [1]–[3], billions of devices will be connected and managed by wireless networks. The vast proliferation of mobile devices which is mainly attributed to the explosive growth of mobile data traffics requirements, such as multimedia traffics. In particular, global mobile data traffics grew 69 percent in 2014. The monthly global mobile data traffics reached 2.5 exabytes at the end of 2014, it will surpass 15 exabytes by 2018 [4]. The very large number of devices with the huge network traffics demands triggers the innovations in architectures and technologies of conventional wireless networks which lead to the fifth generation (5G) of cellular networks [5]. In 5G cellular networks, much mobile data activity takes place within local areas. For instance, in a stadium, the attendees need the match schedules. In workplaces, colleagues require videos, music and gaming. In order to alleviate the load of the base stations (BSs) or access points (APs) including femto-, pico- or micro-enhanced base stations, solutions are necessary for offloading local traffic, meanwhile providing spectrum and energy-efficient local data dissemination.

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Device-to-Device (D2D) communications has been considered one of the key technologies in 5G cellular networks, which facilitates the discovery of geographically close devices, and enables direct, low-power communication between these proximate devices by reusing licensed spectrum resources. Due to the physical proximity and the potential reuse gain, D2D communications can improve spectrum efficiency, reduce power consumption and efficiently offload traffic from the BSs/APs [6].

Recently, energy harvesting technologies have received much interest in 5G cellular networks [7], [8], where wireless devices are enabled to harvest energy from renewable energy sources, such as thermal, vibration, solar, acoustic, wind, and ambient RF signal to prolong the battery life of the battery-equipped wireless devices and improve the system energy efficiency. In D2D communications systems, the conventional energy efficiency improvements include energy-efficient proximity devices discovery, the design of energy-aware resource allocation schemes, and optimal power control for energy-efficient D2D communications. In energy harvesting D2D communications systems, the wireless devices harvest energy from APs [9], then the devices use the harvested energy for D2D communications, when the energy harvesting with high efficiency can power low-energy devices to achieve energy efficient communication and enhance the system outage probability.

On the other hand, social networks and its applications have been widely explored in many fields [10]. The concept of user social pattern has been characterized in LTE-advanced heterogeneous networks to enhance the network spectrum and energy efficiency [11]. Y. Li et al. [12] proposed a social-aware enhanced D2D communications system that exploits social networks characteristics for solving several main technical problems in D2D communications, including mode selection, resource allocation and interference management. The rationale of using social characteristics in D2D communications is that the hand-held wireless devices are carried by mobile users and the knowledge of human social structures and relations can be utilized to establish stable D2D links in order to achieve system performance improvement.

The existing network architectures and technologies have treated energy harvesting and social characteristics as two separate aspects in D2D communications. In this paper, the main contributions are summarized as follows.

- We propose a social-aware energy harvesting D2D communications architecture which integrates energy harvesting technologies and social networking characteristics into D2D communications.
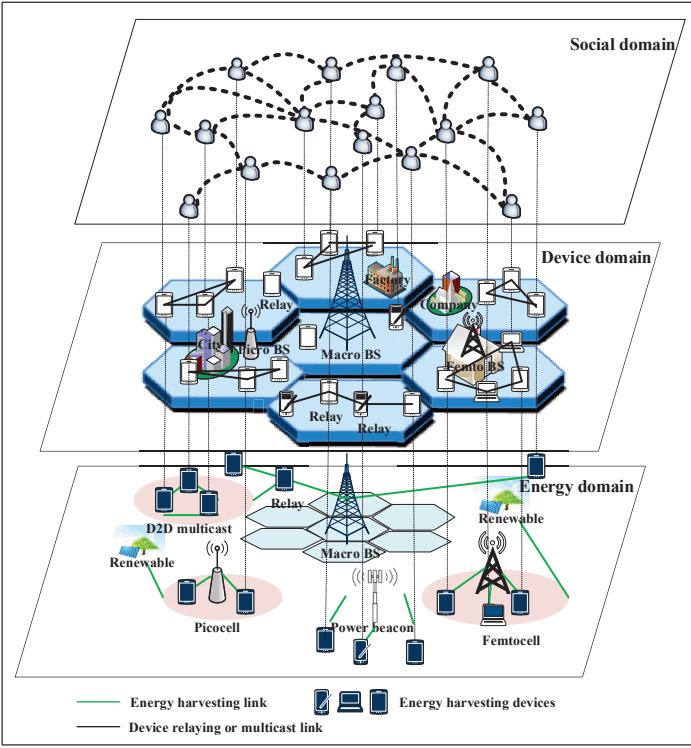
Fig. 1: The proposed social-aware energy harvesting D2D communications architecture.

- The proposed architecture includes three domains: the device domain, the energy domain and the social domain. The interactions among these three domains are also analyzed.
- In the proposed architecture, we mainly focus on the efficient local data dissemination, and propose two social-aware energy harvesting D2D communications schemes: a social ties based energy harvesting device relaying scheme and a social community based energy harvesting device multicast scheme.

The remainder of this paper is organized as follows. In the following section, we present the proposed social-aware energy harvesting D2D communications architecture, along with the key technologies of D2D communications and energy harvesting and main characteristics of social networks. Next we focus on the local data dissemination issues in the proposed architecture and propose two social-aware energy harvesting D2D communication schemes. Then we evaluate the performance of our proposals. The conclusions are presented in the final section.

II. PROPOSED SOCIAL-AWARE ENERGY HARVESTING D2D COMMUNICATIONS ARCHITECTURE

The proposed social-aware energy harvesting D2D communications architecture is shown in Fig.1, which includes three domains: the device domain, the energy domain and the social domain. The key technologies and characteristics of the three domains are explained and the interactions among these three domains are also analyzed.

A. Device Domain

The device domain is shown in the middle of Fig.1. The *device* may refer to smart phones, tablets, e-book readers and any other portable wireless device. When a device is in a congested area or in a poor coverage area, this device can communicate with its destination via the cooperation of relays, which are another devices between the source device and the destination. Device relaying makes it possible for the devices in a network to function as transmission relays for each other to extend network coverage and improve spectrum efficiency. While when devices are in dense areas, such as workplaces, some of the devices have already received the popular content, such as videos and music, via direct BSs/APs connections, these devices can disseminate the received content to the remaining interested users though multicast, which is an efficient data dissemination paradigm delivering the data traffic to multiple devices simultaneously so as to relive the load of the BSs/APs and reduce the system energy consumption. The device relaying and device multicast are two local data dissemination scenarios and are possible with D2D communications functionality, which allows these devices to directly communicate with their nearby devices.

Despite the obvious advantages of higher spectrum efficiency and lower energy consumption, several issues arise in the device relaying and the device multicast dissemination scenarios. Specifically, the availability of the device relaying and the device multicast links relies on the physical proximity between devices. However, the existence of a neighbor may not necessarily imply that a stable device relaying and device multicast link can be set up because the connection may drop due to device mobility. Furthermore, if the neighbor is a stranger, it may not be willing to participate in the device relaying and the device multicast dissemination due to overheads, such as energy consumption. Thus proper incentive mechanisms are essential to stimulate the devices to help others or multicast local content.

However, prior to the incentive problem, there are fundamental aspects that need to be addressed toward efficient local data dissemination. Recent studies have identified peer and service discovery is the first step to start D2D communications [6]. This context information is still important in the device relaying and the device multicast dissemination scenarios, where the wireless devices must be aware of other devices in proximity that either disseminate or request the local traffic. In addition, the device relaying and the device multicast can take place in the dedicated spectrum or reuse the licensed spectrum. Although reusing the licensed spectrum is a more spectrum-efficient communication, it poses complex interference between cellular users and D2D users.

In the implementation of the device relaying and the device multicast dissemination, the aforementioned peer discovery and interference problems can be managed with the BSs/APs control or without any control. In particular, when there is no BSs/APs control, the peer discovery and interference management are the complicated and energy consuming procedure which may involve interaction with the end users. On the other hand, the control of the BSs/APs can significantly
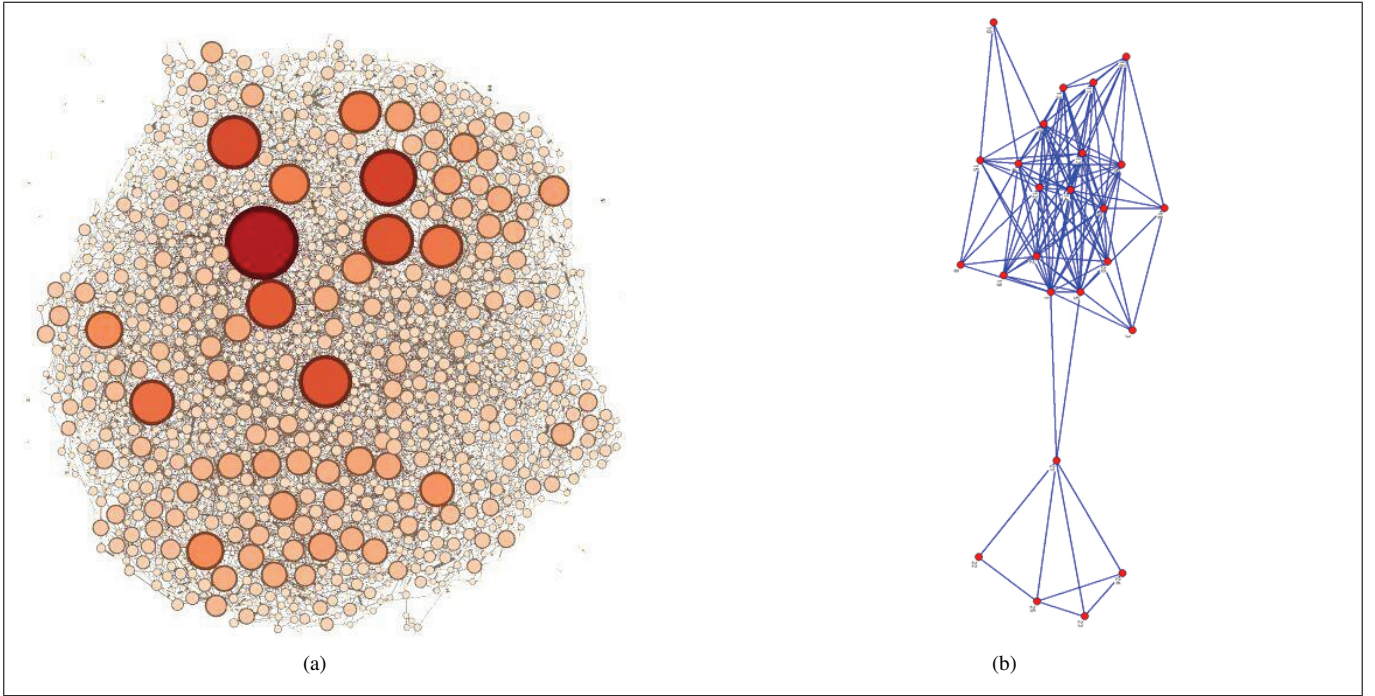
Fig. 2: a) Social structures and relations observed from large scale real communication traces from CDMA2000 cellular networks of China Telecom; b) Social structures and relations observed from experimental traces.

facilitate peer discovery and avoid interference through efficient scheduling and radio resource allocation by exploiting the network information, such as the knowledge of current network load, channel condition and potential D2D pairs. Although the BSs/APs control causes some signal overheads, it is more beneficial in efficient local data dissemination.

B. Energy Domain

The energy domain is illustrated in the lower part of Fig. 1. All devices are equipped with an energy harvesting circuit which enables the devices to harvest energy from environmental energy sources (e.g., solar and wind energy), from power beacons which are dedicated stations that radiate out-of-band microwave signals to power devices, and from ambient radio signals (e.g., RF energy harvesting) with reasonable efficiency over small distance. Contrary to the traditional view, which treats RF interference as a detrimental phenomenon. In our proposed communications architecture, the aforementioned complex interference in device domain is considered as a source of green energy, and can be harvested by the energy harvesting devices to extend batteries lifetime and improve the system energy efficiency.

In addition, a combination of different energy harvesting schemes, such as time splitting, power splitting and antenna switching, can be utilized by energy harvesting devices. The harvested energy can be used for D2D communications or communicating within a small cell. Sakr et al. [13] proposed an energy harvesting based D2D communications system model where the D2D transmitter harvests energy from ambient interference and uses one of the channels allocated to cellular users (uplink or downlink) to communicate with the corresponding D2D receivers. A stochastic geometry tool was used

to evaluate the performance of the proposed communication system. The results indicated that energy harvesting can be a reliable alternative to power D2D transmitters while achieving acceptable performance.

In the device relaying and the device multicast local data dissemination scenarios, energy harvesting can be considered as one of the efficient incentive mechanisms, in which instead of using own power to disseminate local content, the devices can utilize the harvested energy to relay or multicast the local content.

C. Social Domain

In wireless communications, the concept of social networks defines the structures and relations among the mobile users. The main social structures and relations include social ties, community, centrality and bridge [12], where social ties identify the weak or strong connections among individual mobile users. Social community is formed by clusters or groups of mobile users sharing the same interests or behavior, or having close social ties in a local area. Centrality indicates the importance of a "node" within the networks, a central user typically has a stronger capability of connecting other members in the network. A bridge acts as the interaction edge between two adjacent communities for information exchange.

To observe social structures and relations among mobile users, large scale real communication traces were collected from CDMA2000 cellular networks of China Telecom (one of the three operators in China with more than 186 million mobile subscribers). The observation data set for the social relations among the users was chosen from Nanjing, a metropolitan city in China. These large scale communication traces record the

users' contact duration and contact frequency in one month. By analyzing the interaction behaviors among the mobile users, a visualization of social network is depicted in Fig. 2(a), in which the nodes represent the mobile devices held by users. We can observe that each node has different size and color. Nodes with bigger size and darker color have stronger social ties with other nodes. The nodes with stronger social ties can offer more communication contacts than those with weak ties, which also indicates that these nodes are important in the networks and have stronger centrality. However, the social structures of community and bridge cannot be easily observed due to the huge number of mobile users. In particular, the communities are divided according to the strength of the social ties among the users. A clustering algorithm is normally used to divide the communities. It is difficult to process the social ties among the mobile users by using the clustering algorithm when there are millions of mobile users.

Hence, we focus on a real-world mobility data traces Sassy [14], which were collected from a human mobility experiment conducted at University of St. Andrews for 79 days. A total of 27 T-mote devices equipped with an IEEE 802.15.4 interface were deployed among 22 undergraduate students, 3 postgraduate students, and 2 staff members of St. Andrews. For detecting encounters between people, each invent devices were programmed to broadcast a beacon every 6.67 seconds. When other devices detected these beacons, they recorded the timestamp and other information (such as signal strength) for this beacon. The timestamp, the device ID, and other information form a Sensor Encounter Record (SER) that was uploaded to a central database. By analyzing the SER, we plot a visualization of social network in Fig. 2(b), we can observe that two groups of individuals form two communities. When information is exchanged between two adjacent communities, the social bridge is formed. Fig 2(a) and Fig 2(b) are mutually complementary to observe complete social relations and structures.

The observed social structures and relations can be considered as another incentive mechanism and utilized to establish stable device relaying and device multicast dissemination links. For example, in the device relaying scenario, the device which has stronger social tie with the source device can be selected to relay the information of the source device. In device multicast scenario, a user multicasts the required content to a group of users in the same community.

D. Interaction Among Device Domain, Energy Domain and Social Domain

In our proposed social-aware energy harvesting D2D communications system, the three domains interact with each other to perform the local data dissemination.

The interaction between the device domain and the energy domain: the wireless devices use the harvested energy to perform D2D communications, while the amount of the harvested energy is affected by the energy conversion efficiency of the wireless devices, the transmit power of the energy sources and the distance between the wireless devices and the energy sources.
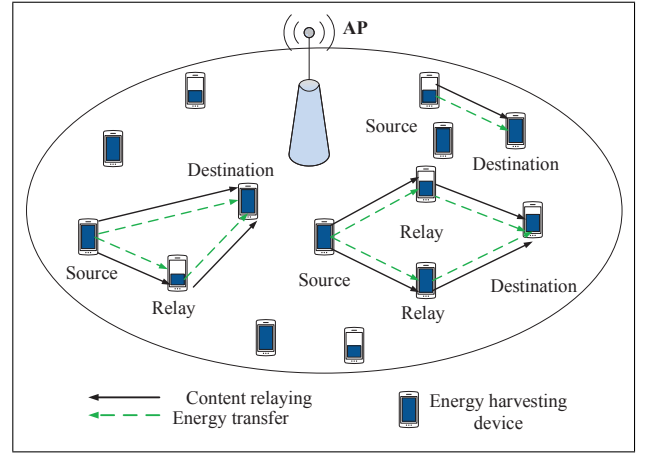

Fig. 3: Social ties based energy harvesting device relaying model.

The interaction between the device domain and the social domain: the wireless devices establish stable D2D links by utilizing the social characteristics; the successful D2D communications enriches the contact data, which facilitates the collection of social information.

The interaction between the energy domain and the social domain: the collection and the transmission of the social information need to consume the harvested energy. On the other hand, the social information assists the D2D communications, which facilitates the wireless device harvesting energy from RF signal.

One domain may affect the other two domains. For example, in the device domain, the energy conversion efficiency and the geographic location of the wireless devices affect the energy harvesting of the wireless devices in the energy domain. Meanwhile, the contact information of the wireless devices, such as the contact duration and the contact frequency, affect the social structure and relations of the wireless devices in the social domain. A careful design among the three domains can lead to efficient local data dissemination.

III. OUR PROPOSED SOCIAL TIES BASED ENERGY HARVESTING DEVICE RELAYING SCHEME

In this paper, we propose a social ties based energy harvesting device relaying scheme in which the devices deployed with an energy harvesting module will relay the source devices information to the corresponding destinations. Moreover, we consider the devices harvest energy from ambient RF signal including the RF interference and store the harvested energy into their batteries. We also consider energy harvesting heterogeneity, which is defined as different abilities to harvest energy from ambient RF signal for different devices. In addition, different devices may have distinct strength of social ties with the source devices. Thus a device which stores sufficient energy for data dissemination and has stronger social tie with source device can be selected as a relay. The specifications of the proposed social ties based energy harvesting device relaying model is in Fig. 3.

We define a set $\mathcal{N}$ with N number of devices. If the n_{th} device ($n \in \mathcal{N}$) would like to communicate with its destination
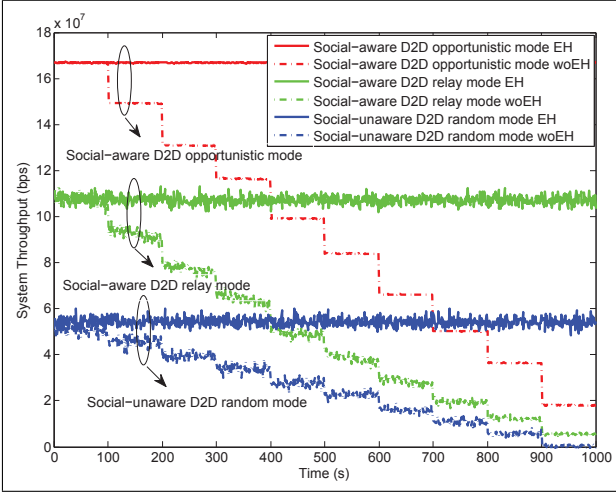
Fig. 4: Comparison of the system throughput achieved by the three transmission modes with energy harvesting (EH) and without energy harvesting (woEH).

Fig. 5: Social community based energy harvesting device multicast model

in the same set by device relaying, this device first sends a device relaying request to the AP. The AP computes the strength of social ties between the n_{th} device and its contact objects according to their average contact duration and the corresponding variance value. Furthermore, the AP exchanges the physical location and the energy information with the contact objects of the n_{th} device. The m_{th} ($m \in \mathcal{N}$) device, which stores sufficient energy to support data dissemination, is physically closer and has stronger social tie with the n_{th} device, is selected as relay. The transmission time is divided into time slots. In each time slot, the n_{th} device can choose to transmit data directly to its destination or to cooperate with the selected relay m_{th} which is defined as the D2D opportunistic transmission. Compared with the traditional D2D communications with AP coordination, the overheads of the AP in our scheme are mainly due to the exchanged energy information between the AP and the wireless devices. In terms of real implementation, the wireless devices can add their energy information in an uplink frame, and then the AP checks the energy information of the wireless devices. The energy information exchange imposes relatively small signal overheads for the AP which is normally powerful with sufficient energy supply.

Our objective is to maximize the system throughput achieved during $\mathbb{T}$ time slots by designing device transmission mode subject to the physical proximity constraint, the strength of social ties constraint and the energy harvesting constraint. The harvested energy for each device $\mathcal{H}_n(t)$ at time slot t is modeled as an independent and identically distributed sequence of random variable with mean $\mathbb{E}[\mathcal{H}_n(t)] = \mathcal{H}_n$. Let B_{min} denote the minimum energy for each device to support the data dissemination, and B_{max} denote the maximum capacity of the rechargeable battery for each device. We model a neighboring graph to elaborate our proposed social ties based energy harvesting device relaying scheme. The neighboring graph is a union of a physical graph, a social graph and a energy graph.
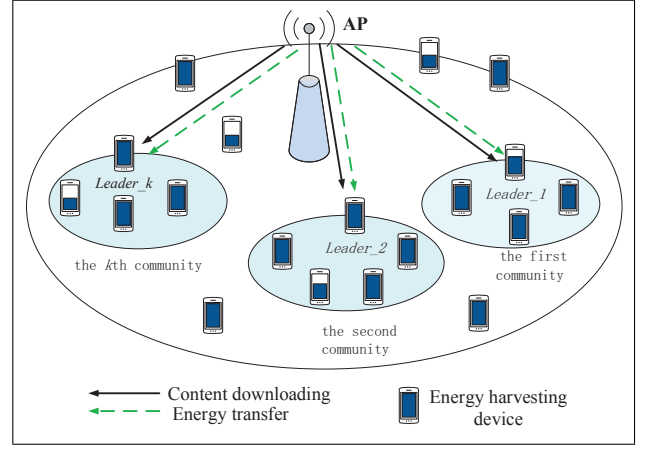
Physical graph - Due to the physical constraints such as physical proximity, only the devices that are close enough can be feasible relay candidates for the n_{th} device. To take such physical constraints into account, we introduce the physical graph $\mathcal{G}^P \triangleq \{\mathcal{N}, \mathcal{E}^P\}$ where the set of nodes $\mathcal{N}$ is the vertex set and $\mathcal{E}^P \triangleq \{(n,m) : e_{nm}^P = 1, \forall n, m \in \mathcal{N}\}$ is the edge set where $e_{nm}^P = 1$ if and only if the distance d_{nm} between node n and node m is smaller than the distance threshold d_{thrd}. The set of nodes that can serve as a feasible relay of node n is denoted as $\mathcal{N}_n^P \triangleq \{m \in \mathcal{N} : e_{nm}^P = 1\}$.

Social graph - The social graph $\mathcal{G}^S \triangleq \{\mathcal{N}, \mathcal{E}^S\}$ is modeled to show the strength of the social ties among the nodes. The set of nodes $\mathcal{N}$ is the vertex set and $\mathcal{E}^S \triangleq \{(n,m) : e_{nm}^S = 1, \forall n, m \in \mathcal{N}\}$ is the edge set where $e_{nm}^S = 1$ if and only if node n and m have a social tie with each other and the social strength w_{nm} is bigger than the threshold w_{thrd}. Here, we define the social strength w_{nm} bigger than the threshold w_{thrd} as strong social tie, otherwise, it is a weak social tie. The set of nodes that have strong social ties towards node n is denoted as $\mathcal{N}_n^S \triangleq \{m \in \mathcal{N} : e_{nm}^S = 1\}$.

Energy graph - The energy graph $\mathcal{G}^E \triangleq \{\mathcal{N}, \mathcal{E}^E\}$ is modeled to show the energy information of the candidates. The set of nodes $\mathcal{N}$ is the vertex set and $\mathcal{E}^E \triangleq \{(n,m) : e_{nm}^E = 1, \forall n, m \in \mathcal{N}\}$ is the edge set where $e_{nm}^E = 1$ if and only if the stored energy of node m is bigger than B_{min} which represents sufficient energy to support the data dissemination. The set of nodes that have sufficient energy to forward the data of node n is denoted as $\mathcal{N}_n^E \triangleq \{m \in \mathcal{N} : e_{nm}^E = 1\}$.

A. Illustrative Results

We consider a single small cell with coverage radius of 200 m. The D2D channel is based on office/indoor scenario. The power level of the AP is 10 w [15]. The devices are uniformly distributed in the coverage area. We construct the physical graph $\mathcal{G}^P$ by setting $e_{nm}^P = 1$ if and only if the distance d_{nm} between node n and m is not greater than 100 m. We use the experimental data trace, introduced before, to simulate the social ties in the considered scenario. The threshold of the social strength w_{thrd} is set to be 0.5. The maximum capacity
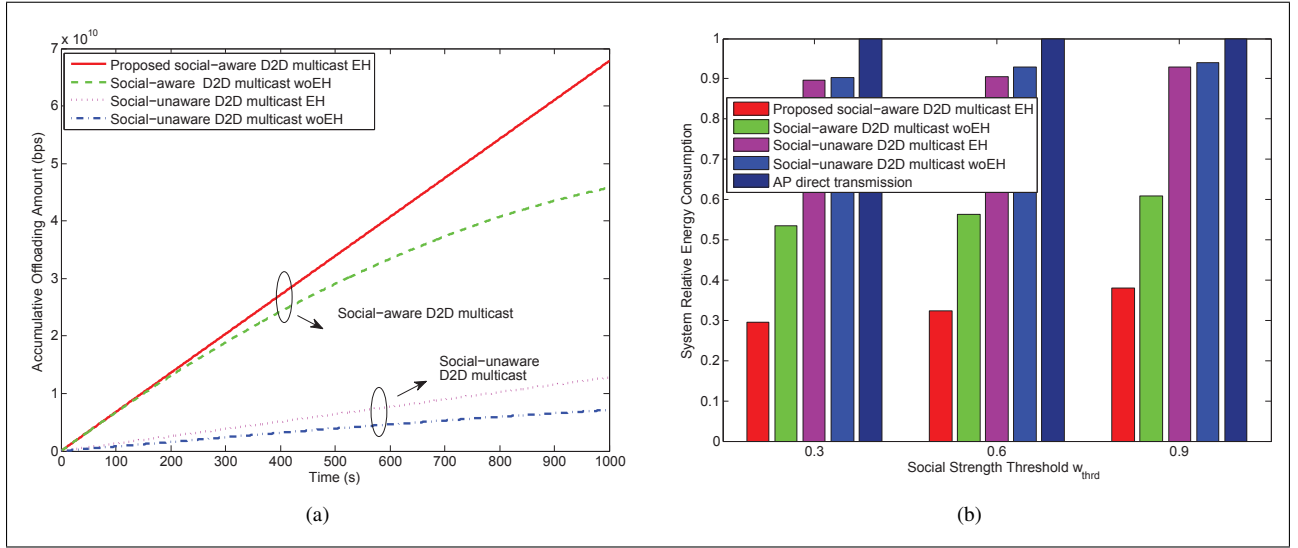
Fig. 6: a) Comparison of the accumulative mobile data traffic offloading amount from the AP; b) Comparison of system relative energy consumption (relative to the energy consumption of the AP direct transmission).

of the rechargeable battery for each device B_{max} is 1000 mAh. The minimum energy for each device to support the data dissemination B_{min} is 0.1 J. The channel bandwidth is 5MHz. The length of a time slot is 1 s. In addition, the initial energy for each device is generated randomly meeting the battery capacity constraint.

System throughput improvement : We compare the system throughput achieved by the proposed social-aware D2D opportunistic transmission, the social-aware D2D relay transmission, and the social-unaware D2D random transmission with energy harvesting and without energy harvesting. In the social-unaware D2D random transmission, the source device communicates with its destination by randomly selecting the direct transmission or the device relaying transmission.

Fig. 4 clearly indicate that the proposed social-aware D2D opportunistic transmission with energy harvesting achieves the highest system throughput when the data dissemination latency is 1000 s. The performance of the social-aware D2D relay transmission is superior to the social-unaware D2D random transmission, since the randomly selected relay may be not willing to help the source device due to the weak social tie. With the increase of data dissemination latency, the three transmission modes with energy harvesting achieve stable system throughput, while the system throughput of the counterpart schemes without energy harvesting decreases. This can be explained as follows. With increasing dissemination latency, the source devices and the relays consume more and more energy for data dissemination. In the three transmission modes with energy harvesting, the devices can compensate the energy consumption by energy harvesting, while in the counterpart schemes without energy harvesting, the devices utilize the energy until all the energy is exhausted. These results demonstrate that both the social relations and the energy harvesting play an important role in the device relaying data dissemination.

IV. OUR PROPOSED SOCIAL COMMUNITY BASED ENERGY HARVESTING DEVICE MUTLICAST SCHEME

In our proposed social community based energy harvesting device multicast scheme, users deployed with an energy harvesting module would like to multicast their received content to the remaining interested users in the same community. We define the users who have received content through direct AP connection as leaders, and the remaining interested users as members. Moreover, we consider the leaders harvest energy from ambient RF signal including RF interference and store the harvested energy into their batteries. Different leaders have different abilities to harvest energy from ambient RF signal. In addition, different members may have distinct strength of social ties with the leaders. Thus each member joins a community in which the leader has sufficient energy for multicasting, the member has strong social tie and close physical location with the leader. The social community based energy harvesting device multicast model is depicted in Fig. 5. A heuristic community formation algorithm is proposed as following:

Step1: At the beginning of the D2D multicast session, the n_{th} member first sends a content downloading request to the AP. Then the AP computes the strength of the social ties between the n_{th} member and its contact objects according to their contact list. Furthermore, the AP detects the physical location and the energy information of the contact objects. The k_{th} contact object, which stores the required content, and meets the energy, the physical location and the strength of the social tie constraints, is selected as a leader. The AP feedbacks the leader index to the n_{th} member.

Step2: If the n_{th} device can join multiple communities at the same time, it joins the community that provides the highest multicast rate. After all the members have selected their communities, the AP allocates the licensed spectrum resource to each community, and the multicast is performed.

Step3: If a device cannot join any community, it will

download content directly from the AP.

A. Illustrative Results

In this section, we compare the system spectrum and energy efficiency improvement of the proposed social-aware D2D multicast scheme and the social-unaware D2D multicast scheme with energy harvesting and without energy harvesting. In the social-unaware D2D multicast scheme, the device randomly join a community. The wireless parameters are the same as in the device relaying case.

1) System spectrum efficiency improvement: Fig. 6(a) compares the accumulative data offloading amount from the AP of the proposed social-aware D2D multicast scheme and the social-unaware D2D multicast scheme with energy harvesting and without energy harvesting. It is noted that with the increase of the content downloading latency, the social-aware D2D multicast scheme with energy harvesting can offload most of the mobile data traffic from the AP. Thus the AP can use these unused spectrum resources to provide other wireless services so as to improve the spectrum efficiency. The performance of the social-unaware D2D multicast scheme with energy harvesting is worse, because the member randomly joins a community, in which the leader may not provide multicast services due to the stricter social ties constraint. In their counterpart schemes without energy harvesting, with the increase of the downloading latency, more and more leaders exhaust their energy, thus the accumulative offloading amount of the mobile data traffic increases slowly.

2) System Energy efficiency improvement: Fig. 6(b) compares the system relative energy consumption of the proposed social-aware D2D multicast scheme and the social-unaware D2D multicast scheme with energy harvesting and without energy harvesting. At the same social strength threshold w_{thrd}, the relative system energy consumption of the proposed social-aware D2D multicast scheme with energy harvesting is the lowest. While in the counterpart schemes without energy harvesting, more and more communities are unavailable due to the exhaustion of the leaders' energy, thus the members have to download content directly from the AP which increases the system energy consumption. With the increase of the social strength threshold w_{thrd}, the number of members that cannot join the community increases due to the weak social ties which also leads to the increase of the system energy consumption. These results demonstrate the significant energy efficiency improvement of the proposed social-aware D2D multicast scheme with energy harvesting.

V. CONCLUSIONS

In this paper, we proposed a social-aware energy harvesting D2D communications architecture which integrates the energy harvesting technologies and social networking characteristics to improve the spectrum and energy efficiency for local data dissemination in 5G cellular networks. We focused on the efficient local data dissemination issues, and proposed two social-aware energy harvesting D2D communications schemes: the social ties based energy harvesting device relaying scheme and the social community based energy harvesting device multicast scheme. Illustrative results indicated that the proposed device relaying scheme effectively improved the system throughput. In addition, the proposed device multicast scheme achieved significant improvements in spectrum and energy efficiency.

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