

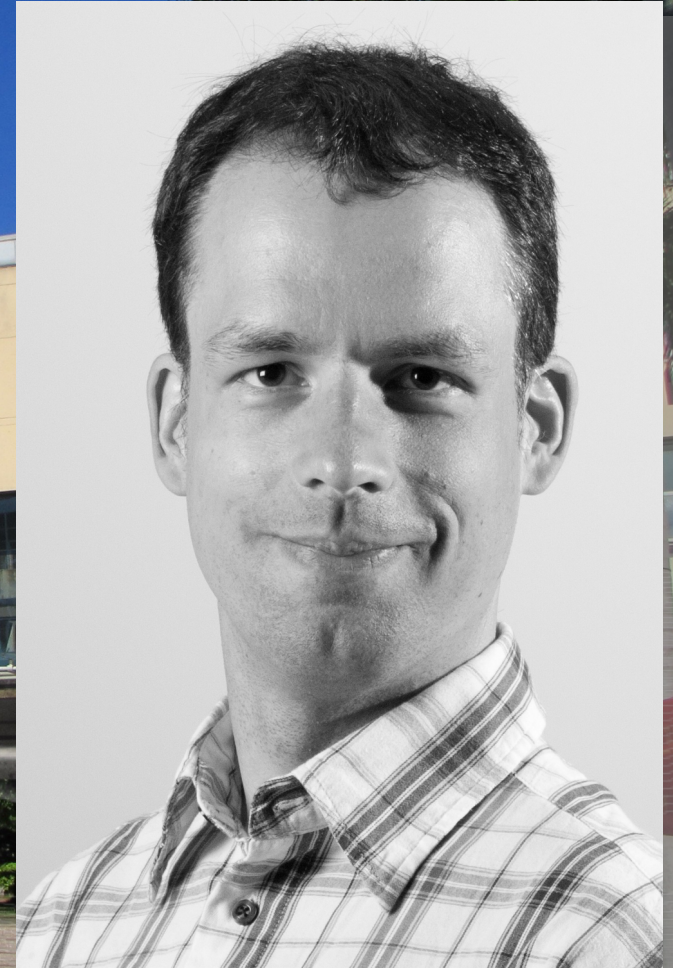
Keynote Talk at Hainan University (海南大学)

An Introduction to Multi-Path Transport at Hainan University

Thomas Dreibholz (托马斯博士)

Simula Research Laboratory

14 December 2017



Contents

- About Norway and the Simula Research Laboratory
- From TCP to Multi-Path Transport
- Simulations
- Lab Setups and Internet Setups
- The NorNet Testbed
- Conclusion
- Literature

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About Norway and the Simula Research Laboratory

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Where is Norway?



Germany 德国

Oslo 奥斯陆

ca. 7,100 km

ca. 8,700 km



Beijing 北京

Haikou 海口

ca. 16,000 km



Sydney 悉尼

Facts about Norway

Capital: Oslo

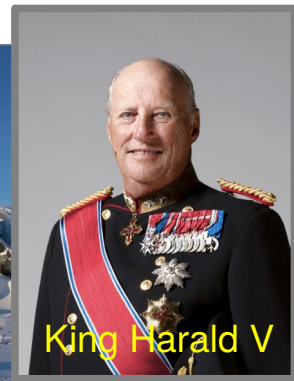
Size: ca. 385,000 km²

Population: ca. 5,214,000

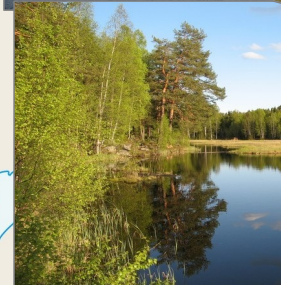
Internet TLD: .no



The Kingdom of Norway (Kongeriket Norge)



King Harald V



The Simula Research Laboratory

- Located in Fornebu
 - Just outside of Oslo
 - In the IT Fornebu complex
- Public limited company
 - Non-profit research organisation
 - Ca. 160 people from all over the world
- Research groups
 - Scientific Computing
 - Software Engineering
 - **Resilient Networks and Applications**
- Norway's leading place for computer science research

[**simula** . research laboratory]



Visit <https://www.simula.no> for further information!

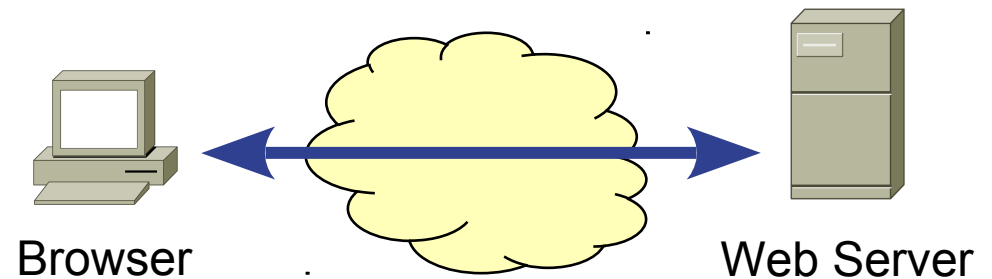
Overview:

From TCP to Multi-Path Transport

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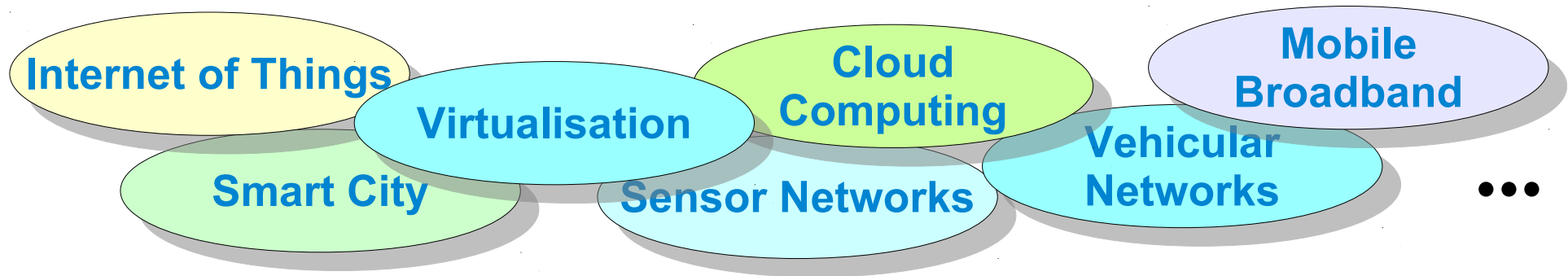
„Classic“ Internet Communication

- Example: World-Wide Web



- Client ↔ Server Communication
 - 1 network interface per device → 1 **IPv4** address
 - Communication with Transmission Control Protocol (**TCP**)

The Current and Future Internet: The Big Picture



- IPv6
 - Devices are frequently IPv4/IPv6 dual stack
 - Usually multiple addresses per interface
- Mobility → address change
- Devices with multiple interfaces
 - Router
 - **Smartphone** (LTE/UMTS, WLAN, Bluetooth?)
 - **Laptop** (Ethernet, WLAN, LTE/UMTS?)



Multi-Homing and Multi-Path Transport

- Multi-Homing
 - Multiple interfaces (addresses)
 - **Redundancy** → Communication even when some paths fail
- Multi-Path Transport
 - Also utilise paths simultaneously → better throughput
 - **MPTCP**: Multi-Path TCP
 - **CMT-SCTP**: Concurrent Multi-Path Transfer for SCTP

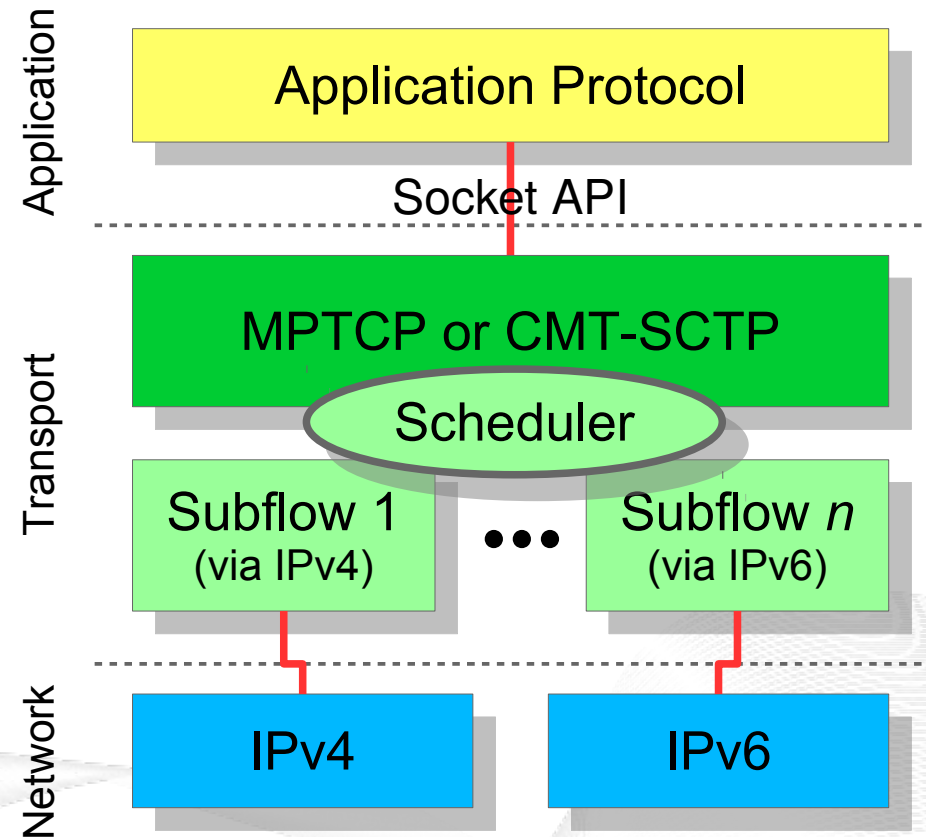


SCTP: Stream Control Transmission Protocol
TCP: Transmission Control Protocol

Hot topic in research and standardisation!

Multi-Path Transport with MPTCP and CMT-SCTP

- Subflow $\leftrightarrow$ path
- Fairness
 - Paths may overlap (fully oder partially)
- Scheduling
 - Different path characteristics
 - Bandwidth
 - Latency and jitter
 - Packet loss



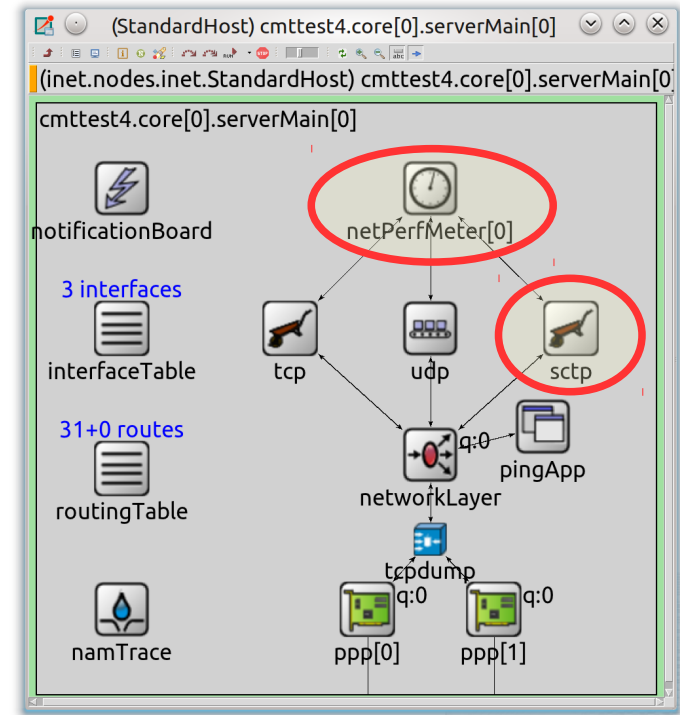
Complex system $\rightarrow$ analyses are necessary!

Overview: Simulations

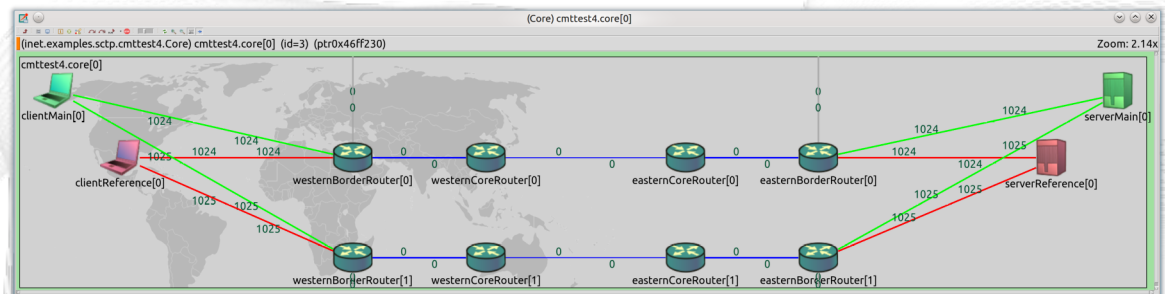
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Research (1) – The Beginning: Simulations

- SCTP in OMNeT++
 - SCTP extensions
 - Application model “**NetPerfMeter**”
- Open Source
 - Mostly part of the OMNeT++ INET Framework
 - Some parts still need merging

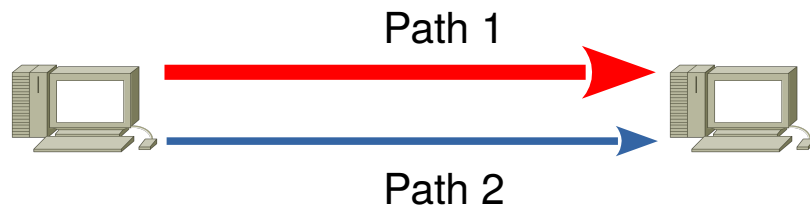


<https://inet.omnetpp.org>



Challenge: CMT-SCTP over Dissimilar Paths

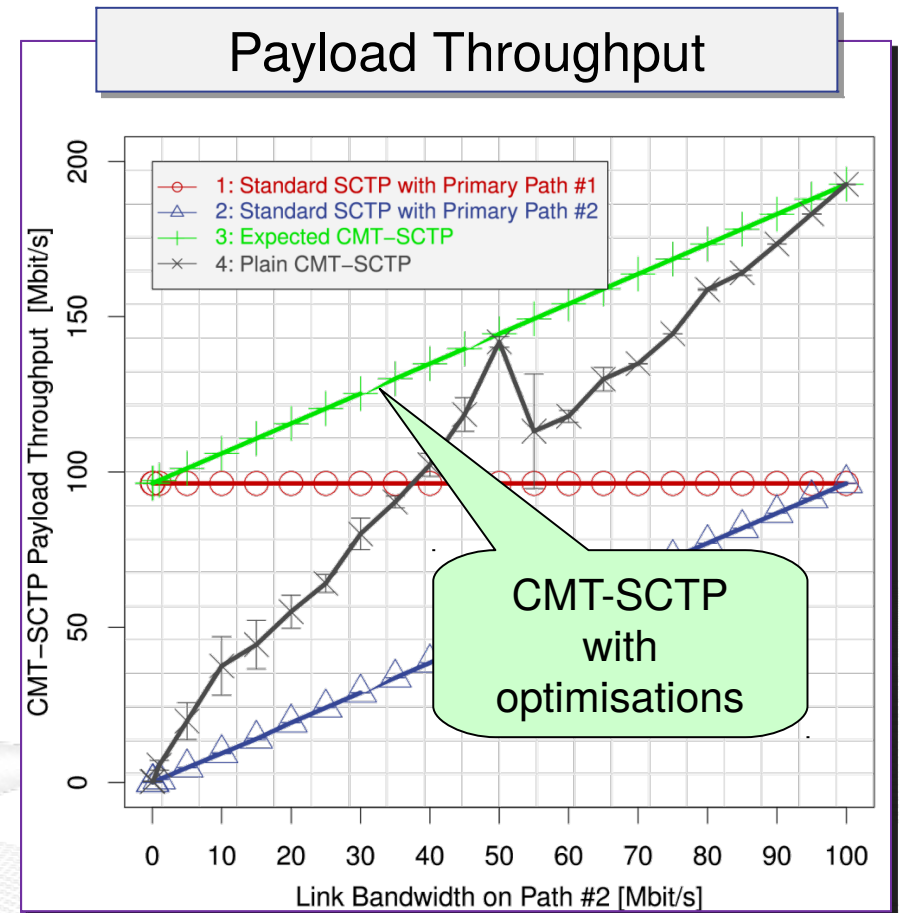
■ Setup



- 2 paths;
100 Mbit/s, 1 ms, 0% packet loss
- Saturated sender
- Bandwidth variation on path 2

■ Simulation results

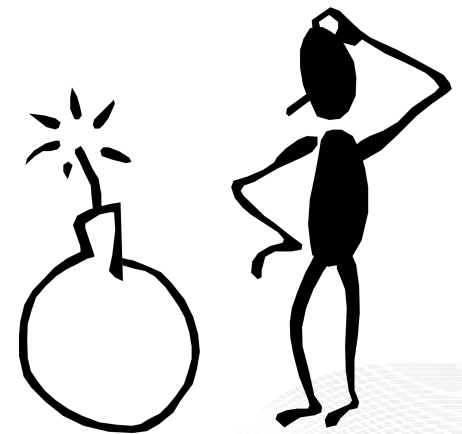
- **SCTP**, primary path via Path 1
- **SCTP**, primary path via Path 2
- **Expected for CMT-SCTP**
- Original CMT-SCTP



Lesson learned: interaction among mechanisms

Efficient CMT-SCTP over Dissimilar Paths

- **Complexity** due to **interaction** of different mechanisms
 - Congestion control
 - Management of send and receive buffers
 - Handling of retransmissions
 - Acknowledgement mechanism
 - Options for message delivery (in-sequence? lossless?)
- Need for a lot of research



How „good“ are the simulations? Comparison to real system!

Overview:

Lab Setups and Internet Setups

- About Norway and the Simula Research Laboratory
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Research (2) – The Next Step: Lab Setup

- Surprisingly big effort:
 - Strange effects of cheap network components:
„It's only cheap on the paper!“
 - Debugging of SCTP in FreeBSD
- But valuable:
 - **The simulations were useful!** 😊
 - Bugfixes for the FreeBSD community
 - Open Source software „**NetPerfMeter**“
 - **Learning effects** and **new ideas!**



Internet protocols → testbed in the Internet!

Research (3) – Real Internet: 3 Cities and 2 Continents



- 3 connected lab setups
 - Establishment of an international cooperation
 - **Essen, Burgsteinfurt** (FH Münster), **Haikou 海口** (Hainan University)
- Very interesting scenario:
 - CMT-SCTP and MPTCP evaluation
 - Very different path characteristics
→ Ideas for further experiments

Many new ideas!

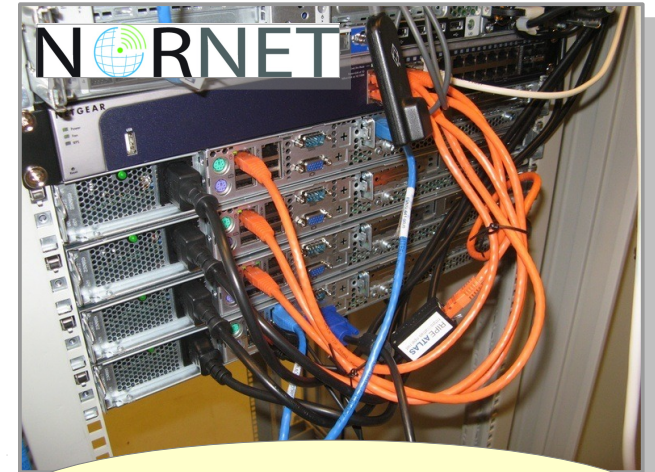
Now really big: NorNet testbed!

The NorNet Testbed

- NorNet Core
 - Cable, up to 4 providers, IPv4+IPv6 (fibre, „consumer-grade” DSL, etc.)
 - Hosts for virtual machines
 - 23 locations (11 in Norway, 12 abroad)

[**simula** . research laboratory]

- NorNet Edge
 - Embedded system „Ufoboard“
 - Up to 4x 2G/3G/4G, 1x CDMA, 1x Ethernet
 - Hundreds of locations (in Norway)



<https://www.nntb.no>



Overview:

The NorNet Testbed

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Goals of the NorNet Project

- Building up a **realistic** multi-homing testbed
- Wired and wireless
 - Wired → “NorNet Core”
 - Wireless → “NorNet Edge”
- **Perform research with the testbed!**



How to get a realistic testbed?

Idea: Distribution of NorNet over whole Norway

- **Challenging topology:**
 - Large distances
 - A few “big” cities, many large rural areas
 - Svalbard:
 - Interesting location
 - Many polar research institutions
- **Deployment:**
 - Core: 11 sites in Norway + CN, DE, SE, US, KR, AU, FR
 - Edge: hundreds of nodes in Norway



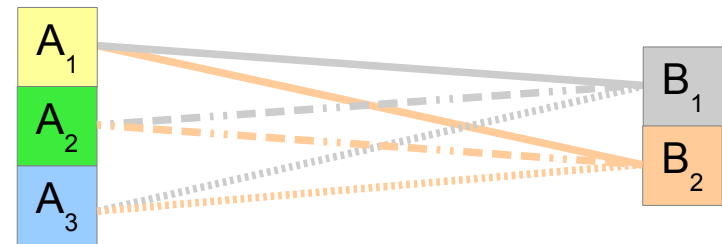
Overview:

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Idea for NorNet Core: Tunnelling

- Researchers require control over used ISP interfaces
 - Which outgoing (local site) interface
 - Which incoming (remote site) interface
- Idea: Tunnels among sites
 - Router at site A: IPs A_1, A_2, A_3
 - Router at site B: IPs B_1, B_2
 - IP tunnel for each combination:
 $A_1 \leftrightarrow B_1, A_1 \leftrightarrow B_2, A_2 \leftrightarrow B_1, A_2 \leftrightarrow B_2, A_3 \leftrightarrow B_1, A_3 \leftrightarrow B_2$
 - Fully-connected tunnel mesh among NorNet Core sites
 - Each site's router (called **tunnelbox**) maintains the tunnels
 - Static tunnels
 - NorNet-internal addressing and routing over tunnels



Address Assignment

- NorNet-internal address spaces:
 - Private NorNet-internal IPv4 “/8” address space (NAT to outside)
 - Public NorNet-internal IPv6 “/48” address space
- Systematic address assignment:
 - IPv4: 10.<Provider ID>.<Site ID>.<Node ID>/24 per site
 - IPv6: 2001:700:4100:<PP><SS>::<NN>/64
(PP=Provider ID; SS=Site ID; NN=Node ID)
- NorNet-internal DNS setup including reverse lookup

Make it as easy as possible to keep the overview!

A NorNet Core Site Deployment

A usual NorNet Core site:

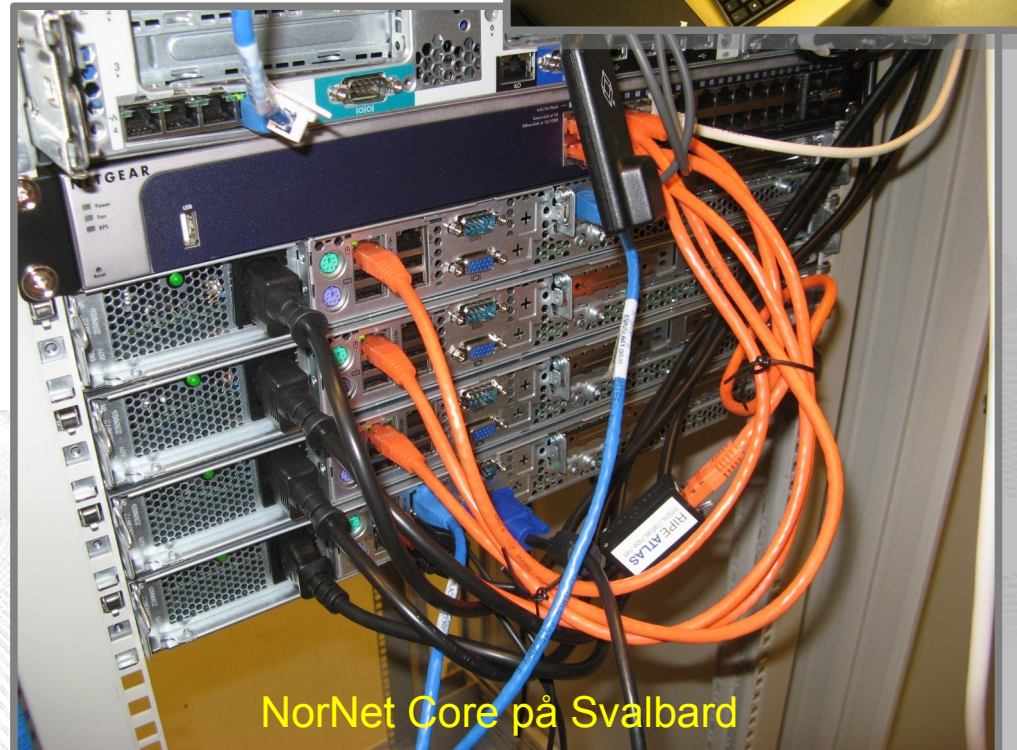
- 1x switch
- 4x server
 - 1x tunnelbox
 - 3x research systems
- At least two ISP connections
 - Research network provider
 - Other providers
- IPv4 and IPv6 (if available)

Additional researcher-provided sites:

- Varying configurations
- VM setups, powerful servers, “retro-style” PCs ...



Longyearbyen 78.2°N,15.6°E



NorNet Core på Svalbard

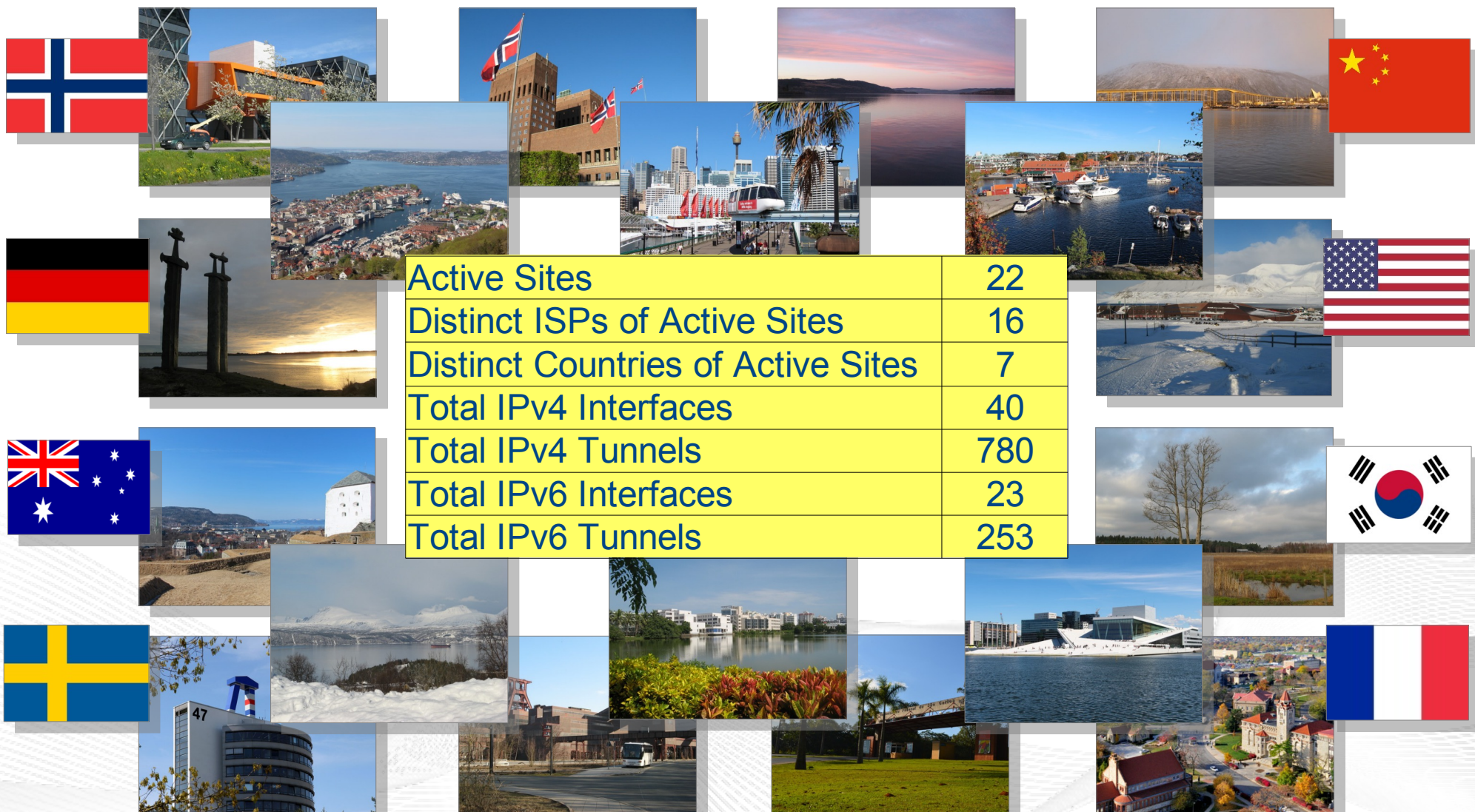
NorNet Core Site Deployment Status (December 2017)

No.	Site	ISP 1	ISP 2	ISP 3	ISP 4
1	Simula Research Laboratory	Uninett	Kvantel	Telenor	PowerTech
2	Universitetet i Oslo	Uninett	Broadnet	PowerTech	
3	Høgskolen i Gjøvik	Uninett	PowerTech		
4	Universitetet i Tromsø	Uninett	Telenor	PowerTech	
5	Universitetet i Stavanger	Uninett	Altibox	PowerTech	
6	Universitetet i Bergen	Uninett	BKK		
7	Universitetet i Agder	Uninett	PowerTech		
8	Universitetet på Svalbard	Uninett	Telenor		
9	Universitetet i Trondheim	Uninett	PowerTech		
10	Høgskolen i Narvik	Uninett	Broadnet	PowerTech	
11	Høgskolen i Oslo og Akershus	Uninett			
12	Karlstads Universitet	SUNET			
13	Universität Kaiserslautern	DFN			
14	Universität Duisburg-Essen	DFN	(Versatel)		
15	Hainan University 海南大学	CERNET	China Unicom		
16	The University of Kansas	KanREN			
17	Korea University 고려대학교	KREONET			
18	HAW Hamburg	DFN			
19	Technische Universität Darmstadt	DFN			
20	Lab. Informatique Grenoble	RENATER			
21	New York University	Lighttower			
22	Haikou Cg. of Econ. 海口经济学院	China Telecom	CERNET		

- IPv4 and IPv6
- IPv4 only (ISP without IPv6 support ☹)
- IPv4 only (site's network without IPv6 support)
- ISP negotiation in progress

<https://www.nntb.no/pub/nor-net-configuration/NorNetCore-Sites.html>

Some Site Statistics (December 2017)



Active Sites	22
Distinct ISPs of Active Sites	16
Distinct Countries of Active Sites	7
Total IPv4 Interfaces	40
Total IPv4 Tunnels	780
Total IPv6 Interfaces	23
Total IPv6 Tunnels	253

<https://www.nntb.no/pub/nor-net-configuration/NorNetCore-Sites.html>

Remote Systems

❄ -30°C
Longyearbyen

Our servers may be really remote!

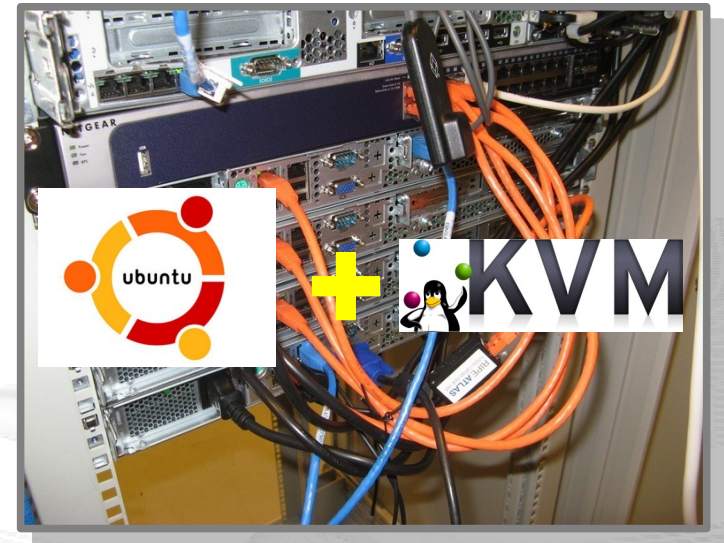


The “road” to Longyearbyen på Svalbard, 78.2°N

Virtualisation

“Anything that can go wrong, will go wrong.”
[Murphy's law]

- Experimentation software is experimental
- How to avoid software issues making a remote machine unusable?
- Idea: virtualisation
 - Lightweight, stable software setup:
Ubuntu Server 16.04 LTS
 - KVM (Kernel-based Virtual Machine)
 - Other software runs in VMs:
 - Tunnelbox VM on physical server #1
 - 2 LXC-based research node VMs on physical servers #2 to #4
 - In case of problem: manual/automatic restart or reinstall of VM



You may use NorNet Core, too!

**Join the tutorial session!
Here, at Hainan University!**

- Contents:
 - Get access to NorNet Core
 - User and slice management
 - Access to slices
 - Using and configuring slivers with own software
 - How to make use of multi-homing?

Overview:

The NorNet Testbed: NorNet Edge

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 - NorNet Edge
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NorNet Edge – Wireless Network Conditions at Heterogeneous Locations



NorNet Edge needs to cover many locations!

NorNet Edge Nodes

Solution: embedded systems instead of servers!

Ufoboard:

- Custom-made for NorNet
- Based on off-the-shelf smartphone board (Samsung Galaxy S)
- 1 GHz ARM Cortex-A8 CPU
- 512 MiB RAM
- 16-32 GB disk (SD card)
- 7 USB ports + Ethernet port
- Debian Linux 7.6 (“Wheezy”)



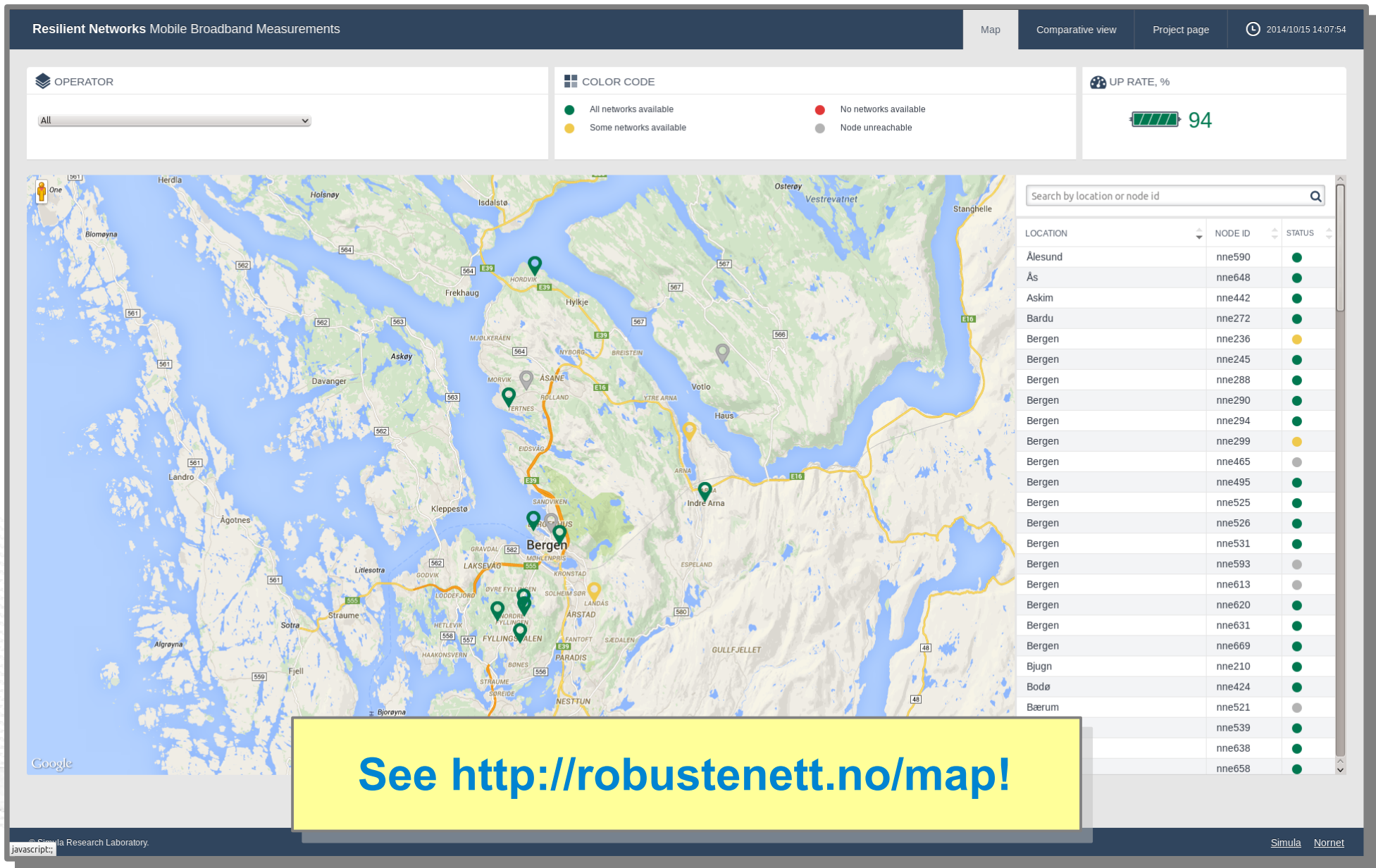
The NorNet Edge Box: Ready for Deployment

Box contents:

- Ufoboard
- Up to 4x USB UMTS or LTE:
 - Telenor, Telia,
 - Network Norway, Tele2
- 1x ICE CDMA mobile broadband
- 1x Ethernet
- 1x WLAN (optional)
- Power supplies
- Handbook



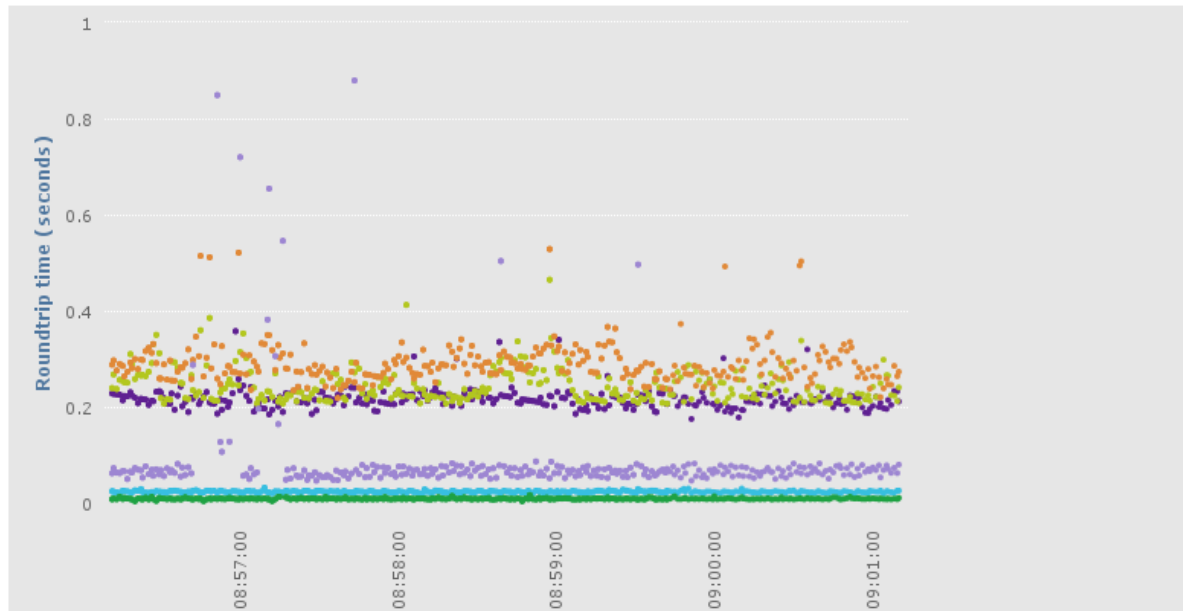
Live Visualisation of NorNet Edge (1)



Live Visualisation of NorNet Edge (2): Real-Time Data and Statistics Database

OSLO, THOMAS'S HOME (NNE497)

LATENCY PACKET LOSS



✓	ISP	STATUS	
←	Telenor	3G (WCDMA)	
←	Netcom	LTE	
←	Tele2	3G (WCDMA)	
←	Network Norway	3G (WCDMA)	
←	ICE.NET	Unknown	
←	LAN	Available	

This plot shows the round-trip time (rtt) for each connection. One 20 byte UDP packet is sent every second to our server, and we record the time it takes before it returns back to the measurement node.

Note that the rtt depends heavily on the mode of the connection. For example, a 3G connection will generally have lower delays than a 2G connection, and an HSPA+ connection will have lower delay than a WCDMA connection. The mode of a connection again depends on the traffic pattern. Hence, sending more traffic can result in a lower rtt.

See <http://robustennet.no/map!>

Overview:

Conclusion

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Conclusion and Future Work

“The road to hell is paved with unused testbeds.”
[James P. G. Sterbenz]

- The NorNet Core testbed is ready for experiments!
 - Do you have experiment ideas? → Talk to us!
- Future work:
 - NorNet Core
 - Additional sites, more IPv6 endpoints
 - **OpenStack support**
 - Improve and refine management software
 - Get more users, may be you?



Visit <https://www.nntb.no> for further information!

“NorNet wants to be a building block of
the railroad to heaven” ...



... and not be another unused testbed that paves the road to hell!

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Literature (1)

- **Dreibholz, T.; Ferlin, S.; Alay, Ö.; Elmokashfi, A. M.; Livadariu, I. A.; Zhou, X.:** “MPTCP Experiences in the NorNet Testbed” (TXT, 25 KiB), IETF, Individual Submission, Internet Draft draft-dreibholz-mptcp-nornet-experience-03, March 30, 2017.
- **Wang, K.; Dreibholz, T.; Zhou, X.; Fu, F.; Tan, Y.; Cheng, X.; Tan, Q.:** “On the Path Management of Multi-Path TCP in Internet Scenarios based on the NorNet Testbed” (PDF, 379 KiB), Proceedings of the IEEE International Conference on Advanced Information Networking and Applications (AINA), pp. 1–8, DOI [10.1109/AINA.2017.29](https://doi.org/10.1109/AINA.2017.29), ISBN 978-1-5090-6028-3, Taipei, Taiwan/People's Republic of China, March 27, 2017.
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- **Ferlin, S.; Dreibholz, T.; Alay, Ö.:** “Multi-Path Transport over Heterogeneous Wireless Networks: Does it really pay off?” (PDF, 986 KiB), Proceedings of the IEEE Global Communications Conference (GLOBECOM), pp. 4807–4813, DOI [10.1109/GLOCOM.2014.7037567](https://doi.org/10.1109/GLOCOM.2014.7037567), ISBN 978-1-4799-3512-3, Austin, Texas/U.S.A., December 11, 2014.

Literature (2)

- **Golkar, F.; Dreibholz, T.; Kvalbein, A.:** “[Measuring and Comparing Internet Path Stability in IPv4 and IPv6](#)” (PDF, 436 KiB), Proceedings of the 5th IEEE International Conference on the Network of the Future (NoF), pp. 1–5, DOI [10.1109/NOF.2014.7119767](#), ISBN 978-1-4799-7531-0, Paris/France, December 4, 2014.
- **Ferlin, S.; Dreibholz, T.; Alay, Ö.:** “[Tackling the Challenge of Bufferbloat in Multi-Path Transport over Heterogeneous Wireless Networks](#)” (PDF, 820 KiB), Proceedings of the IEEE/ACM International Symposium on Quality of Service (IWQoS), pp. 123–128, DOI [10.1109/IWQoS.2014.6914310](#), ISBN 978-1-4799-4852-9, Hong Kong/People's Republic of China, May 26, 2014.
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Any Questions?



Visit <https://www.nntb.no> for further information!