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Comnet: Annual Report 2013

Sassan Iraji (Editor)

Aalto University
SCIENCE + TECHNOLOGY
REPORT

Aalto University publication series
SCIENCE + **TECHNOLOGY** 12/2014

Comnet: Annual Report 2013

Sassan Iraji (Editor)

Aalto University
School of Electrical Engineering
Department of Communications and Networking

Aalto University publication series
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DEPARTMENT OF COMMUNICATIONS AND NETWORKING
SCHOOL OF ELECTRICAL ENGINEERING
AALTO UNIVERSITY

ANNUAL REPORT 2013

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INTRODUCTION

COMNET IN BRIEF

The Department of Communications and Networking (Comnet) is a multi-disciplinary unit of research and higher education covering communications and networking technology, networking business, and human aspects of communication and communications technology. In its area, Comnet is the largest unit in Finland. Comnet develops communications, information and teletraffic theory and conducts fundamental and applied experimental research in communications and networking technology. In shaping the Internet technology, Comnet is a significant force internationally.

REVIEW OF 2013

DEPARTMENT HEAD'S REPORT

Year 2013 was characterized by change of sign in the department growth. The department of Communications and Networking has been rapidly growing since it was founded in 2008 until 2012. During 2013 our budget was reduced by 20%. The budget drop was mainly due to reduction in basic funding from the University and especially reduced number of TEKES projects which was caused by changes of the TEKES policies that no longer supported well ICT systems related research work.

The impact of drop in funding level was partially mitigated by the use of accumulated overheads. As a result the reduction in headcount was only 12% which was mostly achieved by reducing the offered short term research assistant positions for M.Sc. student.

Even though the available resources dropped, the department managed to make big impact in the research community and the society at large. Some of the highlights from 2013 include:

1) The resolution of a 40-year-old problem on the existence of nontrivial Steiner systems over Galois fields, with applications to error-correction in randomized network coding (jointly with researchers at UC San Diego, Technion, University of Bayreuth, and Darmstadt University of Applied Sciences).

2) Several Celtic projects that Comnet participated received Celtic Awards 2013: MEVICO received Silver Award and HOMESNET received the Bronze Award. CELTIC 100GET project was awarded the Celtic-Plus Innovation Award 2013 for its outstanding performance.

3) Introduction of Netradar platform: Netradar is a free service that provides information about the quality of mobile Internet connections, mobile devices, and protocol performance collected by the end users themselves around the world. (https://www.netradar.org/)

4) In EU FP7 project Cervice Platform for Social Aware Mobile and Pervasive Computing (SCAMPI) OS distributed mobile application platform with a decentralized app store: SCAMPI Apps is a distribution platform for applications that use the SCAMPI opportunistic networking library. With the library, it is possible to create network applications (SCAMPI apps) that work even with no network infrastructure. (https://play.google.com/store/apps/details?id=com.futurice.scampi.market)

June 12, 2014 Riku Jäntti

ADMINISTRATION

PERSONNEL

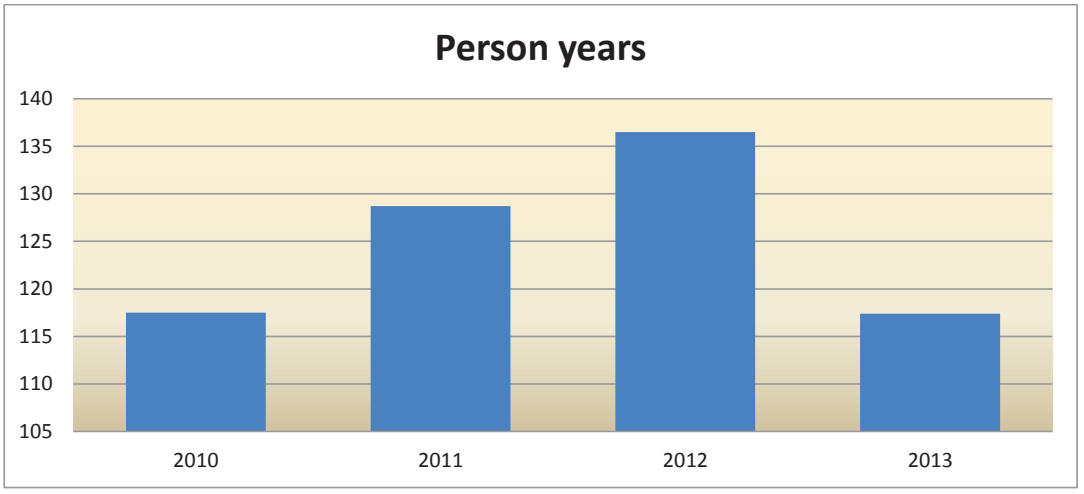


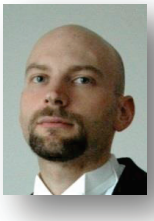
Figure 1: The Development of the person years 2010-2013

Table 1: Personnel structure

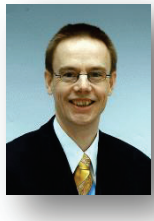
Year	2010	2011	2012	2013
Professors	9	9	9	9
Postdocs	10	10	8	4
Researchers with doctoral degree	8	8	7	9
Doctoral students	62	62	60	56
Research assistants	34	34	41	29
Teaching personnel (incl. part-time)	4	4	4	4
Technical services	5	5	3	4,5
Administration	4,4	4,4	5,5	1*
Total	136,5	136,5	140	116,5

*Administration services are provided by the School of Electrical Engineering.

PROFESSORS



Riku Jäntti
Head of Department



Patric Östergård
Deputy Head of Department

Jyri Hämäläinen

Samuli Aalto

Heikki Hämmäinen

Raimo Kantola

Jukka Manner

Jörg Ott

Olav Tirkkonen

Professors Emeriti

- Sven-Gustav Häggman
- Kauko Rahko
- Jorma Virtamo

IT SERVICES AND MEASUREMENT PLATFORMS

The ICT infrastructure of a department must support a variety of demands set by research and teaching. They create high competence requirements for the support staff and high expectations for the environment compared to a typical office. The needs of research and teaching cannot be met without dedicated and skillful staff that is also able to give good support for normal office computing needs. Having a touch for the "normal" environment is important to keep connection with the reality of ICT organizations and demands set by those environments.

It was seen that department must maintain its high quality day-to-day operations in ICT support to provide the service the research groups need. A workstation migration to Aalto workstations from legacy systems using department and school services was a major project in 2013 and still continues to 2014. Most of "easy" Windows personal computers and common use workstations are now converted to Aalto domain reducing daily support needs for those thanks to automatization of routine tasks. However, all Linux and OSX workstations and many Windows systems used for development work are still under department control. For a foreseeable future many of those will stay outside of central management because of special needs.

Support resources were mostly sufficient for routine daily operations needed to support research and teaching. However, to proactively support researchers and teachers there was not enough time. Resources were short for development in 2013 as two support persons resigned in search for new carriers, one of them was a long-time employee whose contribution over years was a key component for our successful environment. Increase in resources is expected in the first half of 2014 and benefits from Aalto level support for routine basic IT services will hopefully realize.

The department has four major research and teaching facilities in addition to few rooftop locations for radio research:

1) Radio communication research laboratory is a 25 m^2 RF-shielded and RF-anechoic room enabling for measurements for example multiantena systems. There are also few smaller portable chambers for single device tests.
2) Datacenter is used to host most of computing resources and equipment for networking laboratory. In addition it is used to study power distribution, energy efficiency and energy reuse in co-operation with the departments of Electrical Engineering and Civil and Structural Engineering. The datacenter has 57 m^2 raised floor area and 80 m^2 for more ad-hoc test setups.
3) Communications teaching and research laboratory in E3 wing has several work stations and test setups for transmission systems, cable measurements and radio technology like software defined radio.
4) Networking teaching laboratory in G2 wing includes systems from POTS to state of art routers, networking security devices and video conferencing services. The majority of equipment is located in the datacenter and only workstations and user terminals are in G2.

All facilities and rooftop location in Otakaari 7 are interconnected with fiber optic cables making possible to realize direct layer-1 connections if properties of campus 10 Gbit/s Ethernet network are not sufficient.

Our platform for RF measurements currently includes a wideband radio channel simulator, spectrum/signal analyzers, vector signal generators, vector analyzers, a time-domain reflectometer, and multi-channel oscilloscopes. This platform supports measurements with bandwidth up to 80 MHz, in frequency range up to 6 GHz. A software-defined radio platform (a cognitive radio system) is available to implement specialized wireless applications, including MIMO algorithms and protocols. Further improvements are made including new systems for 60 GHz radio area research and measuring coaxial cables and optical components.

Research activities in the department require in part significant processing power; some require large memory while some handle large data sets. To provide for these needs, a computational clusters as well as large storage capacity exceeding 90 TB is available for the researchers. Networking research and teaching needs also a large number of routers and other networking hardware as well as testing equipment. These devices are acquired in part directly by projects, partly from the common budget, and some are also received as donations from equipment vendors and network operators.

Comnet has a direct research network connection to FUNET that was upgraded to 10 Gbit/s in summer 2013. The upgrade proved its value by reducing impact of DDoS attacks towards some services hosted by Comnet. This has proven valuable in developing co-operation with other research institutes and experimenting with new technologies without endangering the integrity and security of the Aalto campus network.

As the research network increases in size, a large part of it is also used for teaching. A large network provides a real-world like environment for students to develop their skills and apply the knowledge they have acquired on lecture courses. Disciplines within the department are continuously integrated to provide full-scale learning environments for students and researchers.

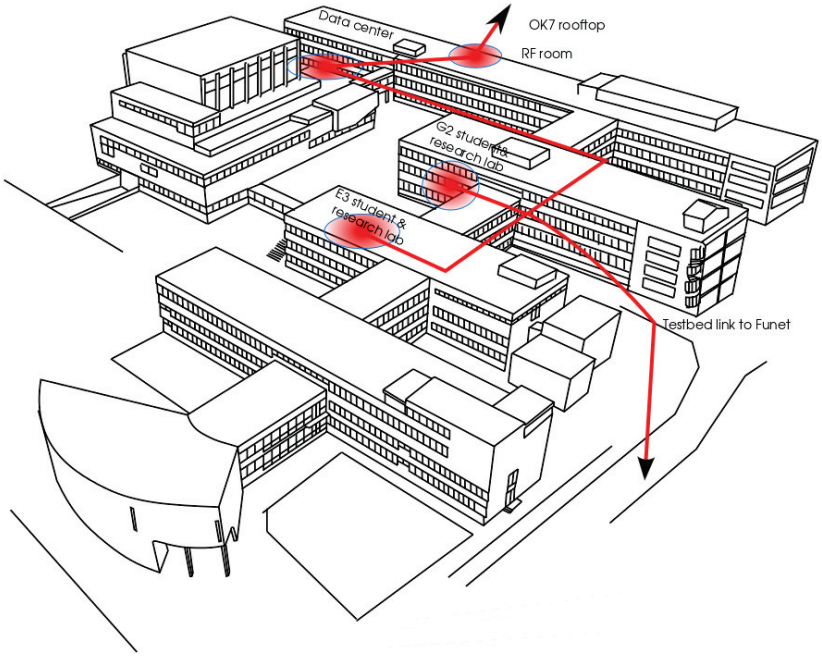


Figure 2: Department research and teaching facilities and fiber optic connections

FINANCIAL ISSUES

EXPENSES AND SOURCES OF FUNDING

Table 2: The Development of the expenses 2010-2013 (€)

Expenses	2010	2011	2012	2013
Personnel	5 580 000	6 087 658	6 637 047	6 039 499
Materials & supplies	234 000	395 085	531 178	184 968
Rents & internal costs	550 000	553 689	587 507	568 909
Other	910 000	930 711	656 464	624 724
Total	7 274 000	7 967 143	8 412 196	7 418 00

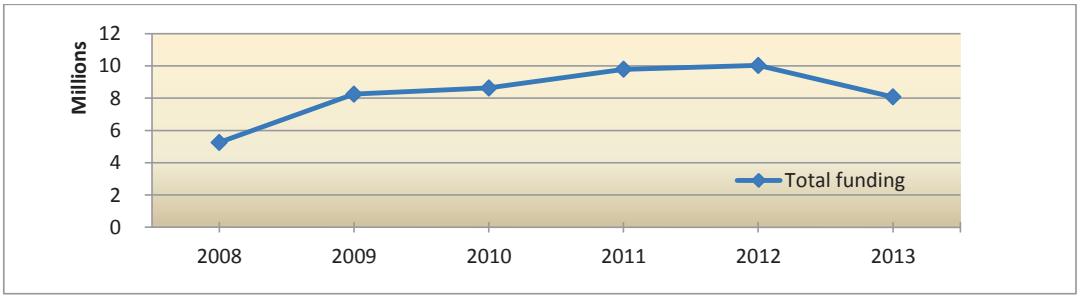


Figure 3: The Development of the total funding 2008-2013

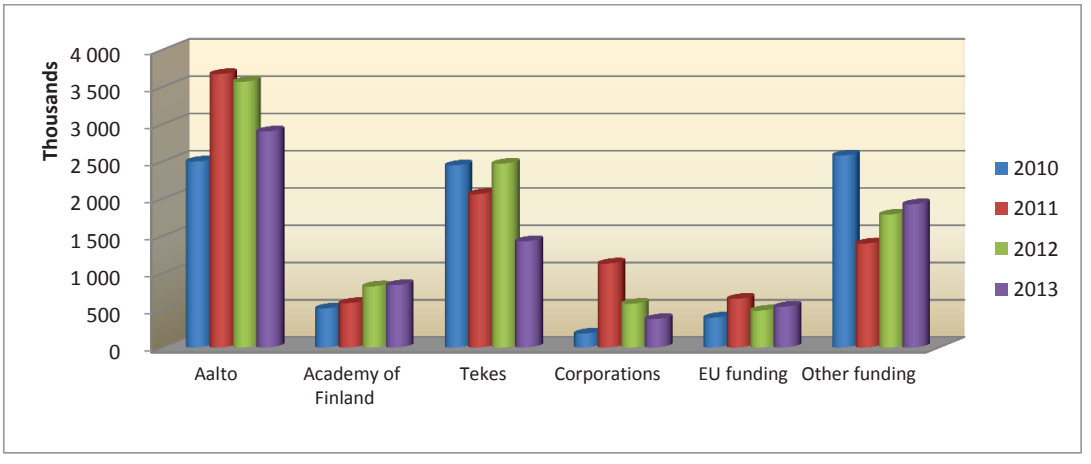


Figure 4: The Development of the funding by funding source 2010-2013

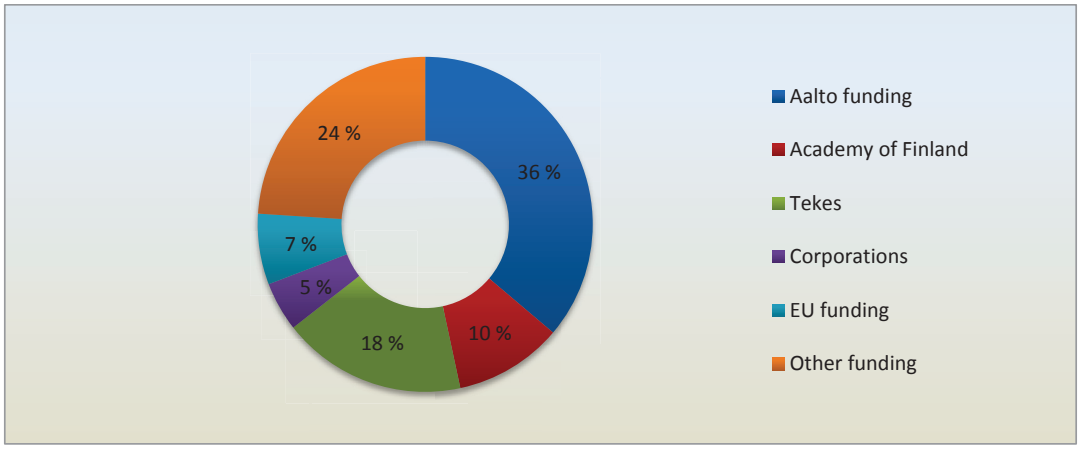


Figure 5: The sources of funding in 2013

SOCIAL IMPACT

Information and Communications Technology is an important exports industry for Finland. ICT is penetrating deeper and deeper all areas of economics and all types of services in the society. Advancement in the growth of productivity in the economy is largely attributed to the use of ICT. This makes the education we give highly relevant for the Finnish economy. The proportion of communications engineering sector among the 100 largest R&D companies in Finland was 77% in 2010. Even if Nokia's share is removed from the figures, the proportion is still 10%. The recruitment of ICT experts in the industry has grown annually about 2% but the growth has shifted from large companies to small and medium size companies.

The social impact can be measured in terms of competence and new knowledge that is produced and used by the economy. Practical measures are how well our graduates are employed and where and with whom we partner in research, as well as the volume of the collaborative research that we conduct.

The high societal impact was recognized as the strongest feature of Comnet in the Research Assessment Exercise by the international review board in 2009. We were graded 5/5 on this measure by the board.

Figure 6 shows that a number of our graduates are employed by the big ICT companies in Finland. At the same time it shows that the graduates spread out widely into the Finnish economy.

We collaborate with tens of Finnish and some foreign companies and organizations in Research projects some of which are organized as collaborative research and some are directly funded by the companies or organizations. We also have important role in helping governmental organizations to develop their networking infrastructure.

In Figure 7 we show the distribution of our research project partners.

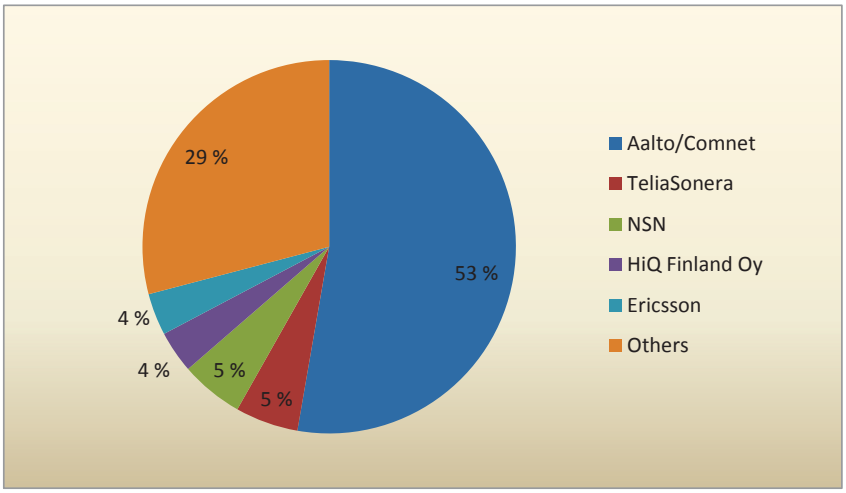


Figure 6: Employers of Master´s thesis students in 2013

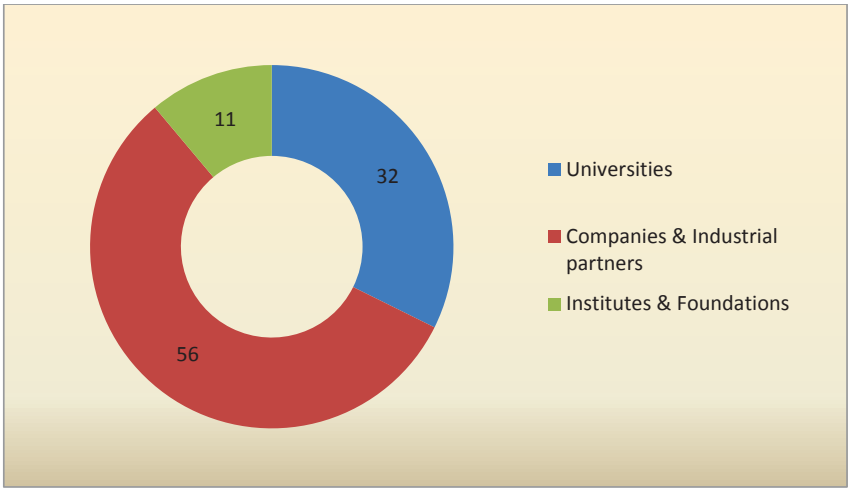


Figure 7: The cooperation – Comnet's partners in projects in 2013

TEACHING

Comnet provides mainly master's and doctoral level education, but also has the responsibility for the courses related to communications and networks (ICT) in the bachelor's level Degree Programme in Electrical Engineering. Having started internationalization of the master's level education in 1999, Comnet is still a main contributor to the competitive International Master's Programme in Communications Engineering, which is attracting talented students from numerous countries.

The Deputy Head of Department is responsible for teaching at Comnet. Prof. Patric Östergård served as the Deputy Head till the end of 2013, when he will be succeeded by Prof. Jyri Hämäläinen. Department-level administration of teaching is based on well-defined job descriptions and the teachers' track at the university. In total 4 teachers of the Comnet department were selected to lecturer career system positions during the year 2013: Doc. Kalevi Kilkki, Doc. Pasi Lassila, Dr. Kalle Ruttik and Dr. Pasi Sarolahti. Also according to university-level policies, teaching is part of the job description of research personnel on all levels.

TEACHING DEVELOPMENT

The annual teaching development day, open to all Comnet employees, took place in August. Various topical themes were handled and particular emphasis was put on the forthcoming reform of the master's level curriculum and its courses (to take place after the reform of the bachelor's level curriculum). The event was well attended and led to various concrete actions.

This year's teaching development day also included a presentation on Enhancing Education and Research in Networking and Communications Engineering (ENhANCE) project delivered by Dr. Edward Mutafungwa. The ENhANCE project presentation provided in interesting perspective of how Comnet department could share some its experiences on the ongoing curriculum reform for the ENhANCE Southern partners, namely: Addis Ababa Institute of Technology (AAiT), Ethiopia, and the College of ICT (CoICT) of the University of Dar es Salaam, Tanzania. The ENhANCE presentation at the event highlighted opportunity for some of the teachers to explore the possibility of sharing some of their teaching materials and research tools for the benefit of the Southern partners. Further details of the ENhANCE project are available at: https://research.comnet.aalto.fi/enhance/

Recurrent basic issues related to teaching include (course) feedback, teaching and assessment methods, and reduction of the number of courses.

Feedback is an utmost important tool in the development of teaching and courses, and various tools for collecting feedback are available. Unfortunately, privacy and legal issues are making it more and more difficult to implement and utilize practical feedback systems effectively.

There is an urge for developing teaching and assessment methods, and teachers are encouraged to implement other methods than traditional lectures and exams. The university provides support in this

process, on all levels up to the extended Aalto University Pedagogical Training Programme. Dr. Markku Liinaharja was among the first Aalto teachers to graduate from that programme.

Reflecting the ongoing bachelor program renewal, and planned master's program renewal, the number of courses taught by the department is constantly decreasing. This action has numerous gains: the employees' teaching load is decreased and the students are guaranteed to get core courses in the field delivered in well-designed packages.

CURRICULUM DEVELOPMENT

The new bachelor's program in Electrical Engineering started in fall 2013.

Comnet is responsible of teaching C-programming, as well as Signals and systems, to all students in the ELEC bachelor's program. In addition, Comnet is responsible for a large part of the Information Technology major in this programme. Comparing with earlier programs, the current program is broader, emphasizes quality on learning and teaching, and promotes student mobility in Aalto. Bachelor's level courses in the new program are lectured in Finnish and the master's level courses are in English.

During 2013, development of new master's programs was initiated in the university. The new programs will start in fall 2015.

INTERNATIONAL PROGRAMMES

Comnet is participating in two international master's programmes. The Master's Programme in Communications Engineering is the oldest international master's level degree programme at Aalto (formerly, TKK) and has been running since 1999, while the International Master's Programme in Communications Ecosystem, launched in fall 2010, is one of the newest. Comnet is responsible for teaching two of the three majors in the Master's program in Communications Engineering. The number of applicants (and enrolments) to these degree programmes have, with small fluctuations, always been on a high level and the students are very good.

International students constitute a significant portion of the total number of Comnet graduates, and many research assistants and doctoral students in Comnet come from the international master's programmes. Currently the intake of domestic and international students is almost equal, while the number of international applicants to master's level programmes annually clearly surpasses the number of native applicants to the full 5-year degree programme. There is a constant increase in the proportion of international graduates at the master's level.

The department has also been active in launching dual-degree programmes with international partner universities of Aalto. The following dual-degree programme is currently active:

- Dual degree in networks and services, with Telecom & Management SudParis, France

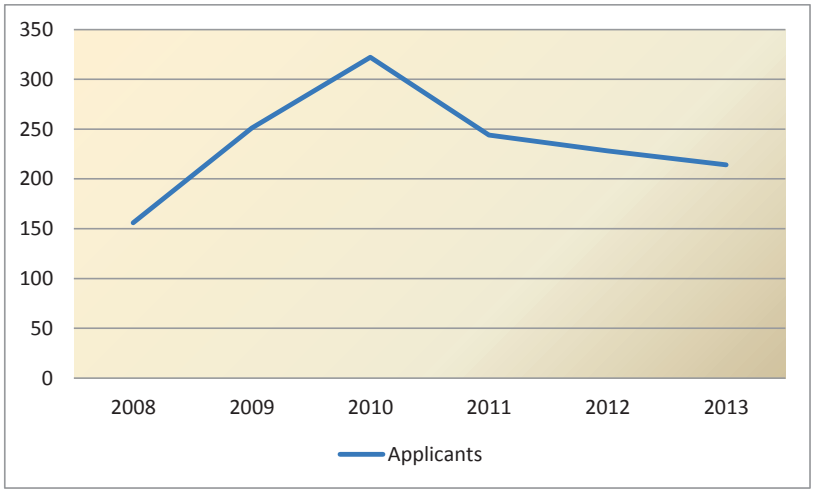


Figure 8: The number of first-choice applicants into International Master´s Programmes on Communication Engineering & Communications Ecosystem

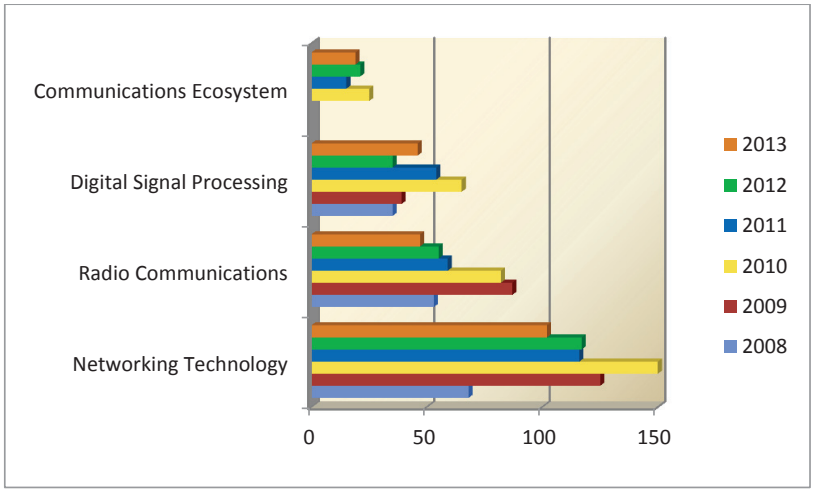


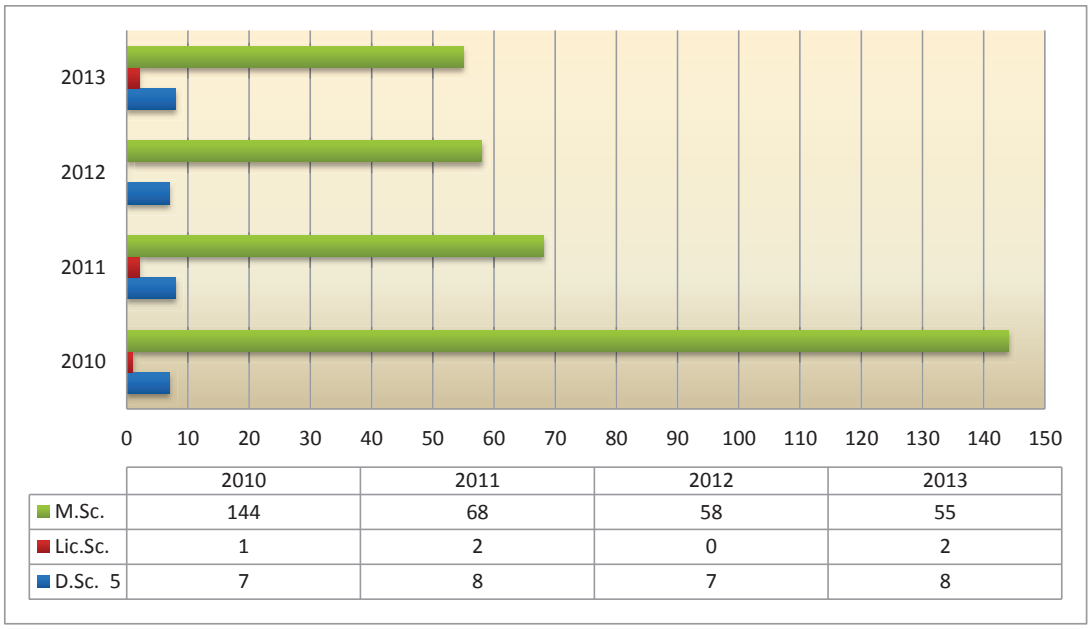
Figure 9: The number of first-choice applicants into international programmes per major. Comnet is responsible for the Communications Ecosystem programme, and the Radio Communications and Networking technology majors.

COURSES IN 2013

ELEC-A7200	Signals and Systems
ELEC-C7320	Software Defined Radio
S-38.1146	Introduction to Performance Analysis
S-38.2121	Routing in Communication Networks
S-38.2131	Networking Technology, laboratory course A
S-38.2131	Networking Technology, laboratory course A
S-38.2188	Communication Networks
S-38.3001	Telecommunications Forum P
S-38.3041	Operator Business P
S-38.3046	Value Network Design for
S-38.3061	Communications Ecosystem Analysis
S-38.3062	Modelling Human Behaviour P
S-38.3115	Signalling Protocols
S-38.3120	Seminar on Communications and Networking
S-38.3133	Networking Technology, laboratory course B
S-38.3134	Networking Technology, laboratory course C
S-38.3141	Teletraffic Theory P
S-38.3143	Queueing Theory P
S-38.3148	Simulation of Data Networks
S-38.3153	Security of Communication Protocols
S-38.3156	Delay-tolerant Networking (DTN)
S-38.3159	Protocol Design P
S-38.3184	Network Traffic Measurements and Analysis P
S-38.3191	Network Service Provisioning P
S-38.3194	Wireless Networks
S-38.3310	Thesis Seminar on Networking Technology
S-38.3455	Challenged Networks P
S-38.3600	UNIX Application Programming
S-38.3610	Network Programming
S-38.4043	Postgraduate Seminar in Network Economics P
S-38.4050	Postgraduate Seminar in Communications and Networking Technology P
S-72.1130	Telecommunication Systems
S-72.1140	Transmission Methods in Communication Systems
S-72.2205	Digital Transmission Methods
S-72.2211	Mobile Communication Systems and Services
S-72.2311	Laboratory Course in Communications Engineering 1
S-72.2410	Information Theory P
S-72.2510	User-Oriented Design of Telecommunications Services
S-72.3216	Radio Communication Systems I
S-72.3226	Radio Communication Systems II P
S-72.3251	Laboratory Course in Communications Engineering 2
S-72.3281	Advanced Transmission Methods P
S-72.3295	Broadcasting and Distribution
S-72.3310	Communication Transmission Lines
S-72.3410	Coding Methods P

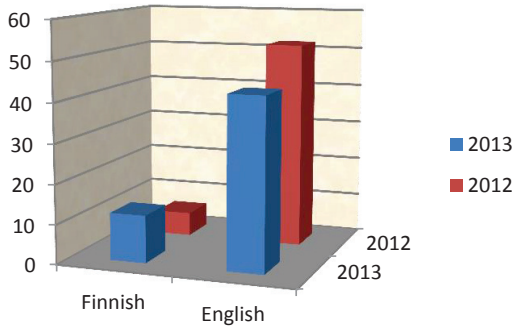
S-72.3510	Product Development of Telecommunication Systems
TLT.kand	Bachelor's Thesis and Seminar
ELEC-A7200	Signals and Systems
ELEC-C7320	Software Defined Radio
S-38.1146	Introduction to Performance Analysis
S-38.2121	Routing in Communication Networks
S-38.2131	Networking Technology, laboratory course A
S-38.2131	Networking Technology, laboratory course A
S-38.2188	Communication Networks
S-38.3001	Telecommunications Forum P
S-38.3041	Operator Business P
S-38.3046	Value Network Design for
S-38.3061	Communications Ecosystem Analysis
S-38.3062	Modelling Human Behaviour P

DEGREES IN 2013



	2010	2011	2012	2013
M.Sc.	144	68	58	55
Lic.Sc.	1	2	0	2
D.Sc. 5	7	8	7	8

Figure 10: Number of degrees at Comnet in 2010-2013



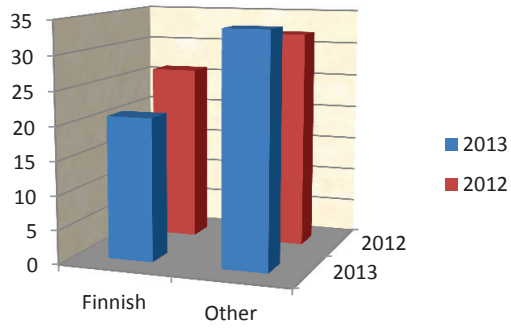


Figure 11: Languages of Master's theses 2012-2013 and Finnish vs. international M.Sc. graduates

RESEARCH

INTRODUCTION (TO RESEARCH)

Comnet carries out comprehensive research in the areas of communications and networking, two areas that have proven inseparable when tackling information exchange at any scale. Its expertise encompasses virtually all aspects of today's and future communication systems and networks.

- The *Communication* part of Comnet addresses research at the "lower layers" of communication systems, enabling and enhancing (primarily wireless) information exchange.
- The *Networking* part of Comnet focuses on creating (global) networks, embracing wireless and core infrastructure networks, and offering suitable communication services and applications on top to satisfy user demands ("higher layers").

These two parts represent the research theme of *Future Networking Paradigms*: architecting future communications and interactions from the transmission of individual bits to networked user applications spanning the globe (and even extending into space). Three *cross-cutting themes* span both parts and provide the fundamental tools to understand and develop these fields:

- *Network economics* captures needs/demands, behavior, and economics of users, operators, and other players in the marketplace.
- *Performance analysis and modeling* investigates characteristics of communications networks by means of traffic measurements and mathematical modeling and develops fundamental algorithms for
- *Information and communications theory:* Communications theory is the bridge between information theory and communications engineering. While information theory provides fundamental capacity limits for the link capacity, it does not provide guidelines on how these capacity bounds could be approached through using real systems that imposes various additional constraints and impairments.

With 9 professors and these complementary research fields, Comnet is well-positioned to approach research in communication and networking in a *holistic fashion*.

The fundamental research themes pursued by Comnet and the specific focus areas described above provide the foundation for strategic research missions following *grand research challenges*. Comnet has identified three such grand challenges we are pursuing in our research as long-term visions:

- *Carbon-neutral networking*: Connecting the remaining global users—2 billion to mobile networks and 5 billion to the Internet—creates, among many others, an enormous challenge in energy efficiency to be able to power wired and wireless network infrastructure, the backend and data center infrastructure, network access equipment, and all the end user devices. We believe that only holistic rethinking of network, protocol, and system architectures can enable this expansion in a carbon-neutral way.

- *Instant wireless Internet*: Internet access anytime, anywhere via wireless networks is becoming increasingly commonplace—provided that users are willing to put up with waiting for their desired content or their interactions to complete, leading to mostly inadequate *Quality of Experience*.

  We pursue a comprehensive approach to future wireless access from the radio technologies to network operation to applications to reduce waiting time to delays below human perception.
- *Scaling the Internet to a thousand devices per user*: Not just the number of Internet users is growing, similarly is the number of their personal devices (for leisure, business, convenience, and medicine) and the number of shared devices penetrating private and public life.

  This will ultimately shift the scale of networking by several orders of magnitude as these devices want to be networked, accessed, managed, and controlled.

Yet another rising theme that will affect our research in the coming years is *cyber and network security*.

ADVANCED RADIO SYSTEMS PROGRAM

VISION AND MISSION

Future 5G wireless systems will allow people to communicate with anyone, anywhere, and at any time using a range of devises and services. Wireless communication will enable self-configuring intelligent home and office systems that can interact with each other and with the Internet. Also widespread wireless sensor and actuator networks are important parts of the development towards all-wireless future and Internet of Things. Our general mission is to carry out world-class research and technology development in wireless communication technologies. Our efforts range from basic research in communications theory to applied research on practical engineering problems.

RESEARCH CHALLENGES

There is a wide span of technical challenges that we must overcome in order to make our vision possible. On our way to future we focus on the following research areas:

- **Flexible spectrum use.** Spectrum sharing is seen as one potential method to improve the efficiency of the spectrum utilization. Many regulators across the world are working towards opening TV bands for secondary spectrum access. The most potential applications of that band are M2M, rural broadband and wireless local area networking. The cellular industry is interested in co-primary sharing and licensed shard access. In secondary sharing case, the incumbent system needs to be protected from the aggregate interference caused by the secondary users. In co-primary case, both systems need to be protected against harmful interference. Interference modeling and control is essential in both cases. Our research focuses on modeling the interference between the systems sharing the spectrum and developing methods for interference control and co-existence. Especially, we focus on impact of very dense deployments and adjacent channel interference effects due to transmission chain nonlinearities.

- **Wireless broadband and system optimization.** The mobile system architecture will undergo a paradigm shift from a centralized, controlled and pre-planned hierarchical system towards self-organizing, self-optimizing ad hoc operation. The driver for this development is the drastically increasing number of cells resulting from the ever increasing capacity need due to wide scale deployment of mobile Internet. Introduction of relays and small cells, such as pico and femto cells and ultra-dense deployments will lead to challenging interference problems that can be tackled by local interference coordination and system optimization. Another important research challenge in future wireless broadband systems is the energy consumption. The increasing data rates and operation bandwidths are pushing up the energy needs in the network. Yet, the energy consumption can be decreased by proper system design, optimization of network operations and dynamic control of cell availability.

- **Software defined radio (SDR) and Cloud based Radio Access Networks (C-RAN):** Software Defined Networking (SDN) has emerged as a new paradigm of network development. SDN provides network owners and developers with open, programmable communication stacks and has changed how we

think about core network design. It is being driven by the bene_ts common purpose servers can provide compared to specialized hardware. Radio access networks(RAN) require similar flegibility to that which SDN brings to core networks. This need is driving the concept of Software Defined Radio Access Networks (SDRAN) and Cloud based Radio Access Networks (C-RAN). A flexible, open and programmable SDRAN could significantly reduce network operation and maintenance costs.

- **Machine type communications:** Machine-to-machine (M2M) communications has been emerged to provide autonomic communication systems for supporting wide variety of intelligent applications. Among various communication technologies, cellular-based systems have been gained more attention as the communication medium for Machine Type Communications (MTC) due to ubiquitous coverage and mobility support. However, the mass deployment of MTC devices in cellular systems is still hindered by challenges arising from different requirements for practical applications. Two different research directions can be identified: Massive MTC and mission critical (real-time) MTC. In the first case the challenge is to make the cellular system scale with large number devices whereas in the latter case the number of devices is smaller but the challenge is to reduce the latencies and maximize the reliability of the communications through the use of ultra-reliable communications.

- **Millimeter wave communications:** Most of the current mobile radio systems operate on overcrowded bands between 450MHz and 3.5GHz. On the other hand, between 3.5GHz and 60GHz there is currently around 7GHz unlisenced spectrum available, including large contiguous bands New access frequency can be made available much more easily on 10-60GHz than below 3.5GHz frequencies. The use of mm-wave communications introduces new challenges due to very different propagation conditions: Received power in isotropic antenna is much smaller in case of high frequencies also diffraction and wall penetration losses become extremely high. Majority of the received signal power comes through Line-of-Sight and first reflected component. Consequently, cell shapes become quasi-deterministic with very sharp edges. Shot noise interference due to overlapping cells become dominant while interference from far away transmitters dies out making cells more isolated. New control structures and network planning methods are needed for efficient use of mm-wave cellular systems.

- **RF sensor networks:** Radio receiver can be viewed as a sensor and lot of information can be inferred from the received signal strength (RSS) measurements. RSS variations due to reflections caused by humans can be utilized to detect a person's presence and movement in the space as well as localize and track it. Also vital signs e.g. respiration rate can be tracked by observing variations in RSS. Tracking moving reflectors can also be used to predict the link quality and to adapt transmission method to the channel conditions in a proactive manner. Even coarse scale signal strength variations could be useful for obtaining relative position of radio receivers in order to make rapid handovers in case of heterogeneous networks consisting of cells of various size operating in different bands.

- **Basic research.** According to our mission we carry out both applied and basic research. The former is executed in subcontracting projects and partly in TEKES funded projects. The latter is carried out in projects funded by the Academy of Finland and TEKES, and as internal strategic research that is conducted by professors and experienced researchers.

MOST IMPORTANT PROJECTS

End-to-end Cognitive Radio Tesbed 2 (EECRT2): This is a TEKES project jointly with Nokia, Fairspectrum, DNA and Ministry of traffic and Communications. The goal of the project is to create a living lab cognitive testbed in Otaniemi, operating on TV white space frequencies, and offering end-to-end cognitive connectivity for test persons. Building and experimenting with the testbed will create new scientific and engineering understanding on the interplay of the technical and economic boundary constraints on the design and regulation of future cognitive radio systems operating on new bands, primarily in the present TV-spectrum. The targeted understanding is of value for regulating authorities, operators, infrastructure vendors, device and hardware manufacturers, with all of these players getting a better understanding of their possible role in a cognitive radio ecosystem. The project is led by Prof. Tirkkonen. Other participants include Prof. Riku Jäntti, Prof. Jukka Manner, and Prof. Heikki Hämmäinen.

Heterogeneous and dynamic wireless access networks (HEWINETS): This is a TEKES project together with Ericsson and Cassidian. The project focuses on radio resource management, interference coordination, and performance analysis of heterogeneous wireless networks consisted of macro, pico, and femtocells as well as nomadic relays. The work is divided into three work packages: WP1 Moving and fixed relays (Prof. Hämäläinen and Prof. Aalto), WP2 Dynamic TDD (Prof. Jäntti and Prof. Tirkkonen), and WP3 Heterogeneous network interference coordination (Prof. Tirkkonen and Prof. Aalto).

Home Base Station: An Emerging Network Paradigm (HOMESNET): This project is part of European CELTIC HOMESNET consortium (15 organizations) and funded in Finland by TEKES, Nokia Siemens Networks and European Communications Engineering. Finnish consortium is led by Aalto University (Professor Jyri Hämäläinen) and second Finnish research organization is VTT. Project focuses on femto base station systems that are characterized by very low costs, plug-and-play installation, low transmission power, use of existing fixed broadband (typically, digital subscriber lines) backhaul and limits access to a closed user group, such as, household members. Mass adoption HBSs will strongly influence the local area evolution.

Energy-Efficient Wireless Networks and Connectivity of Devices – Systems EWINE-S & Densification EWINE-D projects: The main focus of these two sister project is in the mobile network and terminal energy and spectral efficiency. While both aspects strongly depend on the system software and hardware implementations they also depend on the design, planning and management of both network and terminals. In these projects we study Energy and cost effective hardware and technology solutions, novel network planning and service provision aspects, innovative local area, device-to-device and relaying solutions and capacity boost and energy efficiency of heterogeneous networks. The objective is to develop the insight on the key factors affecting to the energy and spectral efficiency, and to design new hardware solutions, algorithms, control structures and network planning approaches achieving the desired objectives. Main results are published as scientific articles in top international conferences and journals. Both projects are carried out in collaboration with the Chinese research projects in Sino-Finland framework.

Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society (METIS): This is a large integrating project funded by the European Union FP7. Participants are from major European mobile network infrastructure and user equipment vendors, operators and universities. The main objective

of METIS is to lay the foundation for a European consensus on the future global mobile and wireless fifth generation communications system. METIS will provide valuable and timely contributions to pre-standardization and regulation processes, and ensure European leadership in mobile and wireless communications. METIS will provide fundamentally new solutions which fit the needs beyond 2020. Comnet role in METIS is to develop methods for flexible spectrum access, coexistence and robustness in multi-band and shared spectrum environments. Especially, we focus on control of aggregate inter-system interference, dynamic spectrum sharing, and spectrum access concepts for device-to-device (D2D) operation.

Networks 2020 (NETS2020): This project started in 2009 and is funded by TEKES, Nokia, Ericsson, Nokia Siemens Networks, Nethawk and Elektrobit. Research organizations are Aalto University (Professors Olav Tirkkonen and Jyri Hämäläinen) and Centre for Wireless Communications (University of Oulu). The research focus is in the future development and evolution of cellular communication systems including IMT-Advanced (IMT-A), its further evolution and its integration with other communication and data networks. The main emphasis is on evolving wireless network topologies, like relay based connections and femtocells. One of the key goals is to develop distributed algorithms performing automated network management tasks. The research is carried out in close cooperation with the best relevant universities and research institutes in China.

Distributed Resource Allocation and Interference Management for Dense Heterogeneous Wireless Networks: This is a joint project with Comnet and University of California and it is funded by Academy of Finland and National Science Foundation. The international research team will address critical deployment issues that arise in Heterogeneous Networks (HetNet) by focusing on the development of distributed and effective mechanisms for resource allocation and interference management in order to facilitate low complexity and decentralized network operation in heterogeneous environments. The project results will facilitate novel technological directions that transcend multiple networks and multiple network layers. In particular, the results will assist the near term deployment of wireless HetNet, including the broad use of femtocell deployment.

Feedback Optimization for Network-level Communication Strategies (FONCS): This is a project at Aalto funded by the Academy of Finland. In the project, optimization of network-level feedback for wireless communication is addressed. The main goals are to construct a closed form analysis framework for optimizing feedback use in the physical (spatial MIMO and power control) and MAC (Channel Quality and Hybrid ARQ) layers. The framework is applied to design efficient and near-optimal feedback schemes for network-level transmission strategies. Practical and implementable feedback designs with direct relevance to the design of future spectrum-efficient wireless communication systems will be constructed. In particular, optimum feedback strategies for multiuser-MIMO (MU-MIMO), Collaborative Multipoint Transmission (CoMP) and Interference Alignment (IA) will be investigated. All of these strategies are particularly vulnerable to non-idealities in feedback, especially in the spatial domain

Robust and Secure Cognitive Radio Networks (Rosecorn): This is a project funded by the Academy of Finland. The main topic investigated is coexistence of secondary users in cognitive radio networks. Secondary users may be associated with different cognitive networks and seek to operate in the same frequency bands. Effective Radio Resource Management as well as security and privacy issues for

cognitive networks are addressed. The project partners in Finland are Aalto University and the University of Oulu, in collaboration with Northwestern University and University of Maryland in the context of the Wireless Finland-US collaboration program.

Reliable and Real-Time Wireless Automation: This is a TEKES project jointly with the Department of Automation and Systems Technology, VTT, University of Vaasa, Konecranes, Metso Automaton, Wapice, Mervento, Vacon, and TK-Engineering. The RIWA project deals with reliable and real-time wireless communication and control systems for industrial wireless automation applications. Applying wireless technologies in industry enables flexible and cost effective automation systems. The primary goal of the project is to develop robust hardware and software components and design tools for industrial applications. The emphasis is on industrial pilots, where the research results of the projects are tested and evaluated. The pilots ensure both a tight cooperation between the research institutes and the industry partners and a guideline for researching and solving the right issues.

Towards Green 5G Mobile Networks (5GrEEn): This is a project funded by EIT ICT Labs. The project partners are KTH, Aalto University, Ericsson, and Telcecom Italia. In 2020, mobile access networks are expected to experience a thousand-fold increase in traffic volume compared to 2010. This calls for a substantial deployment densification. The network will not only target human interaction but also virtually, anything connected following the "Internet-of-Things" vision. Users will require ubiquitous services, provided by efficient mobile access networks and backhaul solutions. The obvious challenge is to provide this thousand-fold capacity increase to billion of devices at today's energy consumption and operating cost levels. Low energy performance needs to be taken into account when the standardization process for 5G takes off. The present approach suggests a new clean slate system architecture with a logical separation between the ability to establish availability of the network and the ability to provide functionality or service. Such architecture is studied in 5GrEEn.

Statistical Modeling and Control of Aggregate Interference in Wireless Systems (SMACIW): This is a joint Academy of Finland and Korea Science Foundation project together with Yonsei University, Korea. In order to optimize the usage of spectrum and support heterogeneous systems and services, many different networks need to co-exist on the available bands. They generate interference to each other. The maximization of the network capacity requires consideration of the interference between the networks. Recently, there have been advances in the analytical modeling of the aggregate interference. Till now aggregate interference models are used only for dimensioning the networks. The models are relatively simple and describe very general network properties. In this project, we will develop new statistical interference models that take into account the impact of terrain, user density, flashlight interference due to advanced transmission techniques, and time variations due to multiple access control mechanisms. The proposed models will then be utilized to derive interference control methods and to perform system capacity analysis.

Interference Management for Wireless Networks beyond Present Horizon (IMANET): The project aims at providing relevant scientific information on general interference management between network nodes that have limited capability to exchange control information with each other. The focus in this project is to optimize the use of radio resources for a multi-antenna cellular system with varying level of coordination between the network elements. In addition, principles and methods for statistical interference management of future heterogeneous networks will be developed, analyzed and tested. Theoretical limits and guidelines for coordinated beamforming and resource allocation across different cells, relays,

antennas, frequency, and time dimensions with different system optimization objectives are provided. Project is joint effort between Centre for Wireless Communications (Oulu) and Aalto University.

OTHER PROJECTS

- Quantitative Assessment of Secondary Spectrum Access (QUASAR), EU FP7, 2010-2012
- Wireless Indoor Situation Modeling II (WISM-II), TEKES project, 2010-2012
- TIEVA-II, Finnish Defense Forces, 2010-2012
- LTE Investigations in MIMO and Other topics (LIMO), Renesas Mobile Europe
- Machine-to-machine Self-organizing Networks, Renesas Mobile Europe
- InterMediate Cognitive Systems (IMCOS), Nokia
- Mobile Media Service Laboratory / Cognitive Connectivity, EIT
- ICT&E, Aalto ELEC energy efficiency program, 2012-2013

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NETWORKING RESEARCH

Professors: Raimo Kantola, Jukka Manner, and Jörg Ott

The area is addressed by three collaborating groups led by each of the professors. The aim is to do world class research into new networking protocols, architectures and solutions arising from broader deployment of wireless technologies, new types of applications delivered over the Internet, the scalability and energy consumption problems and other challenge that are present in the current Internet and the technology push for scaling up the transmission speeds in the Internet.

The Networking Technology Group led by Professor Raimo Kantola has concentrated on routing, switching, measurements, security, and trust management for the Internet. A particular effort has gone into developing a new Internet architecture based on the idea of raising trust to the position of a cornerstone of the architecture. This work has two areas: (1) protecting the interests of the receiver on the level of the basic interaction between communicating parties and (2) collecting evidence of misbehavior and using that to encourage cooperative behavior of the hosts. The first requirement is implemented by Customer Edge Switching and the second by Trust management. Put together we are trying to bring the kinds of methods people and other living organisms use to promote and maintain cooperation in a community to the Internet environment. We present our ongoing work on the architecture on the site: www.re2ee.org.

The Group for Networking Protocols, Software and Architectures led by Professor Jörg Ott pursues the goal of investigating short-term and long-term architectural changes to networked systems and protocols with a focus on transport and application layer aspects. The current two core research themes are: 1) Delay-tolerant networking -inspired architectures and protocols to enable and sustain communications in challenged networking environments and their implications for future Internet design. Instances of such architectures are information-centric networking and mobile opportunistic networking, 2) Adaptive real-time communications for fixed and wireless content distribution and conversational multimedia. Essential elements in research besides modeling and simulations are prototyping applications and experimentation in test beds and the real world. Both themes rely on growing network measurement efforts to understand the evolving Internet traffic patterns, understand deployment options for future protocols, infer (trends in) user demand and user behavior, assess user-perceived quality of experience, and derive mechanisms for improving performance.

The Networking and Transport Group of Jukka Manner has developed a number of technologies to enhance data transport and network connectivity of end hosts, both mobile and fixed. The group has five research themes: 1) evolution of data transport protocols and algorithms, and multipath and multilink data transfer for both fixed and mobile nodes, 2) energy-efficiency of data centers and wireless communications with a specific focus on extending the lifetime of smart phones, 3) Ethernet-based networking extending the IETF-driven TRILL technology (also called Routing Bridges), 4) network and cyber security with a focus on Ethernet-based networks and industrial systems and 5) a new kind of messaging platform for governmental use cases that can connect together old analog communication systems from the 80's with modern digital high-speed and wireless technologies and provide personal, group and geographical message delivery, a kind of DTN-like system. The key test bed and experimental platform is Netradar, available on all major smart phones and the Internet at www.netradar.org .

RESEARCH CHALLENGES

Wireless

Modeling Human-Based Networking and Communications

The is aim to further networking in which humans and their mobile devices constitute the network infrastructure – augmenting, substituting, or bypassing mobile operator infrastructure – to provide additional communication facilities. The key challenges are in human behavior: understanding human mobility as well as patterns for sharing/accessing content and human interactions – and their interrelations. These are needed to devise suitable mobility and traffic models to for evaluating (not just) DTN protocols, but also the overall performance of wireless applications.

DTN Routing, Transport, and Application Protocol Design

Delay-tolerant networks may feature a number of limitations and require rethinking protocols at all layers. Most notably, such limitations include large communication latencies and intermittent or non-existing instant end-to-end paths. While quite a few applications could, in principle, still operate in such environments, their protocol design needs to change: from avoiding frequent end-to-end interactions to novel schemes for pacing traffic (congestion control) and achieving reliability to new security concepts. Routing, transport, and application functionality may require closer interaction, yet maintaining independence as much as possible.

One goal of our work is supporting networking for mobile users without wireless networking infrastructure and in cases when infrastructure access is intermittent or otherwise unreliable. In particular, this means exchanging and sharing information directly between users and their devices, without the costly detour via network infrastructure and cloud services: *opportunistic networking and computing*. We investigate the theoretical foundations, explore novel mobile service and programming paradigms, and build systems for real-world deployment. One key feature of localizing communication is that avoiding relying on infrastructure prevents authorities and service providers from censoring and profiling/tracking users.

Protocols for Lossy Environments

The goal is to develop protocols, algorithms and methods that support communication in challenged environments. These environments include the ISM band where systems and networks are built and operated without proper planning and interference control, environments for sensor networks and special radio networks like PLM. The aim is to create co-operative cross layer mechanisms that suit for particular protocol stacks and to communication middleware.

Power Consumption

Mobile network and device vendors like to advocate constantly higher speeds and the network operators seek to enhance their coverage of the country. Thus, today the consumer is in theory living great times. However, the promises the industry is making are mostly available to e.g. laptop users and devices with high processing power, and large batteries. People carrying smart phones, the most basic and common user of mobile networks, are having problems because the new higher speed offers also consume much more energy than the previous generation. New battery technologies, and e.g. fuel cells, do not necessarily help because higher energy consumption also produces heat, which is undesirable in mobile devices being held

in peoples' hands. Thus, one research area within Comnet is the design and implementation of more power efficient mobile communication, with an emphasis on the network protocols and middleware. A related ongoing topic is the energy efficiency of the other end of the data transport connection, the data centers. With the huge increase of digital services and increasing network traffic, the energy consumption of data centers and in particular the cooling and heat reuse technologies have become very interesting topics.

Core Networks

Research is focused on measuring and analyzing the use of networks, developing and analyzing mechanisms and architectures that are needed in networks for addressing, identification, routing, information delivery.

Ethernet Networking

The background of our work is the ongoing move from synchronous bit stream oriented transmission using PDH and SDH to asynchronous packet based transport in worldwide public networks. This move is taking place due to the tremendous growth of data traffic that overtook voice traffic in volumes soon after year 2000 and due to the lower cost of asynchronous transport. Ethernet is also a popular technology to connect thousands of servers within data centers.

The aims are 1) to develop Carrier Grade Ethernet technology for the use of Ethernet in public services packet networks and 2) to enhance the classical Ethernet technology for broader use in the Internet. Further aims are investigate the security (or lack thereof) of Ethernet and enhance Ethernetworking technology for the purpose of solving the scalability and other problems that are present in the current Internet. Achieving this aim would lead to gradual replacement of IP as the key networking protocol in the Internet.

The footprint of Ethernet is growing. A new technology is 100Gbit/s Ethernet and the use scenarios that emerge with the growing footprint. One new way to leverage Ethernet into new use cases is link aggregation. This is pursued for both access and more generic use cases.

Network Measurements Studies

Network measurements pursue the goals of understanding the characteristics and usage of both existing and future networks and evaluating performance starting from network devices and ending with large-scale networks under different conditions. The challenge in studying existing network traffic is the delicate balance between needs of in-depth information and user's right to privacy. Careful anonymization and strict security procedures are the keys in protecting user's data while keeping information useful for research. Evaluating network device performance is a basic building block for reliable, high-performance networks. Finding scalability related problems in equipment and protocols require full-scale testing either in simulated or in a real network. Scalability of measurement infrastructure is ever important with the increase of link speeds. Finally, infrastructure-based measurements at certain points in the topology yield only limited insight into network operation and performance as experience by the users. Those need to be complemented by large scale measurements based upon end user equipment (for fixed and wireless/mobile networks).

A new service launched by Comnet is called Netradar. It is a crowd sourced mobile network measurement platform with smart phone apps available for Android, iOS, Windows Phone, Meego and Symbian. The

system is distributed in the cloud with presence in EU, US and Asia. Various statistics and maps are presented at www.netradar.org .

Routing Algorithms

The aim is to develop algorithms for computing data structures (e.g. trees) that facilitate routing of packets with minimal cost, so that given constraints are satisfied. We seek to combine basic research on graph theory, algorithms, and computational complexity with practical heuristics and realistic requirements coming from the industry.

End-to-End Transport

Adaptive Real-Time Transport

The communication characteristics of the Internet and wireless (cellular) networks vary over time, calling for adaptive transport and application protocols. As loss patterns and congestion signals vary, different sensing and adaptation mechanisms are needed in protocol design for the respective environments, posing particular challenges as mixed networks become commonplace and (mobile) endpoints can no longer make assumptions about their operating environment. We investigate error and rate control mechanisms for both streaming and conversational multimedia, with a focus on leveraging and enhancing the Real-time Transport Protocol (RTP). This is particularly important with multimedia communication endpoints becoming web browser-based (real-time communication in web browsers, RTCweb), a recent development in the Internet driven by the industry that will lead to an ever faster growth of multimedia traffic.

Large-Scale Multimedia Content Distribution

Moving entertainment services such as TV to the Internet (IPTV) requires the capability of large-scale content distribution – which can be either achieved by ISP-supported native IP multicast or by means of peer-to-peer overlays. Both are conceptually similar one-to-many multicast dissemination of real-time streams, requiring mechanisms for error repair and overall quality monitoring, among others. We investigate network architectures to scale to millions of receivers by applying RTP in these environments and enhancing its feedback, monitoring, and adaptive repair capabilities as needed. We also study the suitability of multi-source and multi-path communication for RTP-based media.

Multipath transport

Until very recently, most of the work on Internet transport has focused on optimizing a single path between the sender and receiver. With the increase in multi-interface mobile devices and a wealth of competing technologies to connect almost any end host and access network, we need to look much more into data transport happening in parallel over multiple paths and links. Our network research has taken a number of focus points in multipath transport, for example, efficient connectivity for multi-interface mobile devices, multipath real-time streaming, multipath TCP, and new ways to provide affordable multihoming to small and medium businesses. We have already a number of prototypes on these topics, and focus on this area is increasing year to year.

Flow and congestion control algorithms

A topic very much related to the development of the networked world is how well the transport protocols do and their algorithms work with mobile users and their devices. For example, the power consumption of

a smart phone is tied to the time the radio equipment is on, not the amount of bytes transmitted. Thus, the faster we can transmit the data, the more we save energy on the mobile device. Moreover, research so far has presented a number of competing congestion control algorithms for communication over wireless links, but there is little work to make e.g. TCP-based transfer adaptive on finer scale and potentially change the used algorithms after each ACK-packet. The overall goal is to design the ultimate congestion and flow control algorithms for mobile devices typically sending small flows over a multitude of wireless technologies.

Networking Applications

Software Defined Networking

During 2013, jointly with industrial partners and in the EIT ICTLabs context, we studied the concept of Software Defined Networking and in particular applied it to mobile networks (LTE and 5G). We developed an experimentation platform and a demonstrator that comprises an eNodeB simulator, SDN-style control plane for LTE networks with mobility management and firewalling functions. The demonstrator can be connected to the Internet and has been presented in several international events. The experimentation platform can be easily extended with new capabilities and used to study the feasibility of applying SDN concepts such the OpenFlow –protocol to mobile networks.

Customer Edge Networking

We carried on to study and prototype the principle of *best effort communications* where the network does its best not only for the sender like in the classical Internet but also for the receiver. Customer edge switching puts powerful policy controlled tools into the hands of the receiver and its edge device to block all unwanted traffic. A multi-homed edge tunnels all traffic through the core network to the other edge where the inbound node can enforce its requirements on the service flow admission. We can view these edge nodes as collaborative firewalls. Customer networks can place their hosts into private address realms. The edge node, with a Private Realm Gateway function, offers legacy interworking for unchanged Internet hosts. During 2013 we developed further the security mechanisms and heuristics for Customer Edge Switching. We generalized the concept of Private Realm Gateway to a Realm Gateway that among other features can translate between IPv6 and IPv4 for the case of single stack IPv6 servers. The prototype/demonstrator of the technology is available to the research community on the site: www.re2ee.org.

Trust Management

We study the application of trust management technologies into mobile cloud computing, unwanted traffic control over mobile Internet, mobile commerce, pervasive social networking, mobile applications, embedded systems, pervasive computing and Internet of things. In 2013, we designed and developed a practical reputation system for pervasive social networking, e.g. for chatting, explored the impact of trust information visualization on mobile application usage, developed a prototype system for unwanted traffic control through trust management for controlling SMS spam and tested its performance with regard to a number of trust related aspects, investigated a distributed unwanted content control solution in MANET through simulations, explored trust of mobile applications based on user behaviors and based on this study developed a usable reputation and recommender prototype system for mobile apps. We also conducted a study of the adoption/acceptance of trust management to control unwanted traffic using game theory.

Privacy Preservation

Protecting user privacy in different contexts such as cloud computing and social networking has become an important topic. Our approach has been to create new schemas for privacy preservation by combining trust management with traditional security techniques with the goal of creating efficient solutions with regard to computation complexity, communication efficiency and key management that can be applied to particular user needs. We also study privacy protection for trust management solutions, privacy protecting data mining, anonymous authentication etc.

Content-Based Networking

A significant portion of Internet traffic is about publishing, sharing and accessing – public and private – content. The present host-centric model of the Internet insufficiently reflects this trend, and caches and overlay architectures have been designed to improve content distribution. We investigate elements of a future content-based (or: information-centric) networking architecture, in which any router may offer generic application support functions such as caching. We have devised optimizations at the edges for content access and sharing (opportunistic cooperation between mobile nodes) and are investigating applying similar concepts to elements of the core network.

Generic Messaging

Governmental, including military, communications typically employ hardware and software that has been designed and deployed for a particular purpose. Often this hardware is rather old, and outdated in terms the current state of the art on communications. Yet, the government organizations still have to use the old hardware for years to come, while looking into upgrading the network with more up to date hardware. There is thus a tremendous need to build whole messaging systems, where new and old hardware can coexist and work together. IP is not an option in this unification because the physical connectivity and hardware are so different, and there is no unified addressing scheme that could be used end-to-end. One major research and development effort in Comnet is building a messaging platform that can merge together any communication technology available currently, or designed in the future, while making sure old legacy hardware can still be used up to its end of life. The high level concept is similar to DTNs in that an end-to-end stable path is not expected, but communication is rather based on messages that are delivered hop-by-hop.

EXAMPLE PROJECTS

Future Internet Research Programme (ICT SHOK)

The Internet connectivity offered to end users, e.g., SMEs is somewhat two-fold: we have commodity class connectivity, e.g., home ADSL, without very high SLA guarantees, and then we have Internet access with SLA guarantees, e.g., 99,99% uptime, but with a high cost. One work item at Comnet is to design a scheme that would enable bundling multiple unguaranteed commodity class connections to form a high-speed connection with an SLA guarantee. Along the technical design, we are also investigating the business models for a virtual ISP and deployment of the technology.

Other important lines of work have concentrated on extending the lifetime of mobile phones by making efficient and intelligent use of the application protocols and wireless connectivity, and on the development of data transfer algorithms and protocols.

100GET

The Celtic 100GET project investigates future core network running at 100 Gbit/s links, and where the network is built over IEEE 802.3 Ethernet, or an evolution of the technology. In Finland, the subproject was composed of industry and research institutes. The focus of our work was on two topics, (1) understanding the scalability of legacy Ethernet and the recent IETF-driven Transparent Interconnection of Lots of Links (TRILL), and (2) extending the standard TRILL framework. This latter topic studies issues such as limiting the amount of broadcast Ethernet frames that is by nature an integral part of the technology, and making the whole network distributed, removing single points of failure and enabling efficient use of multiple routes between ingress and egress Ethernet switches across the core. Future work items in this area include suitable security models for a large Ethernet-based domain, and OAM for Ethernet networks. Recently 100GET was awarded the CELTIC Plus Innovation Award of 2013. In May 2013 the project was awarded the EUREKA Innovation Award in Brussels.

SIGMONA

The “SDN Concept in Generalized Mobile Network Architectures” (SIGMONA), will study network architectures and functions for evolution of the LTE/EPC (3GPP) mobile networks. The main focus is on the network, although and end-to-end system approach, including the LTE radio system, will be taken. The project will apply the latest networking and computing technologies and architectures onto the LTE/EPC mobile network. The project aims at evaluation, specification and validation of a Software Defined Mobile Network concept designed onto the software defined networking (SDN), network virtualization and cloud computing principles. AALTO is taking active role in several work packages and is setting national pilot to integrate the deliverables from the Finnish partners.

ITN METRICS

METRICS is a Marie Curie project where we aim to study the factors that influence our understanding of the performance of the global Internet. The METRICS project is organized around three main scientific lines of work which consists of advanced Instrumentation for Future IP Networks, Big Data Analysis in Support of Advanced Network Management and Operation and APIs and Applications for Advanced Network Monitoring Capabilities.

SCAMPI

SCAMPI is a project in the field of opportunistic and mobile communications, funded by EC FP7 with eight partners from academia and the industry. The main goal of the project was to enable a rich variety of services to be composed from the diverse resources in the mobile users' environment. The project tackles opportunistic service composition both from the theoretical and systems perspectives. This includes building a middleware platform for developing and distributing opportunistic services and applications. The platform and applications are distributed in the Google Play Store and used as a basis for the SIGCOMM 2012 conference application. The platform has become the basis for our work on networking in the PRECIOUS project and EIT ICT Labs (see below). We are working towards its commercial exploitation in cooperation with a Spacetime Networks Oy, a startup by members of Comnet. SCAMPI concluded in the

end of 2013, having produced several further notable applications and a significant number of publications, including multiple best paper awards and a text book. See http://www.ict-scampi.eu/results/

PURSUIT

The Internet communication has become dominantly information-oriented, where users are more interested about "what" information they are consuming, instead of "who" delivers it. The PURSUIT project designed and implemented a novel, secure publish/subscribe information-centric communication architecture for the future Internet, based on the initial work done in PSIRP project. The project investigated various problem areas related to publish/subscribe networking, such as mobility, security and routing. Topics of particular Comnet involvement were, for example: 1) how to design functions that have traditionally been part of the transport layer (such as congestion control) in information-centric publish/subscribe architecture; 2) how naming and content identification should be done in such network, so that an authentic content can be addressed securely; 3) designing strategies for packet-level caching and replication of content, considering the constraints from network resource management and congestion control. PURSUIT was an EU FP7 STREP project of 8 partners, running since September 2010.

EIT ICT Labs

We have a strong role in EIT ICT Labs, being the lead of two Activities (on Opportunistic Networking and SDN) and involvement in several further ones. 2013 was the third consecutive year that we participated in the EIT ICT Labs innovation activity on Software Defined Networking (SDN). The activity provides complementary funding for work that is done in Carrier Projects such as SIGMONA and others. This year the SDN activity is focused in technology transfer and commercialization of the results from previous years. IN the Activity on Mobile Opportunistic Networking and Computing (MONC), we have been paving the way towards commercial grade implementations for embedded platforms and mobile phones using the SCAMPI platform (see above): we established a wireless testbed within Aalto for performance and stress testing and we carried out a productization study in cooperation with the Aalto Design Factory in which a team of students developed the downloadable router concept: liberouter. See http://www.ict-scampi.eu/results/scampi-liberouter/

In the Activity Future Media Cloud, we are developing technology solutions for large-scale media conferencing such as, Web-based Real-time Communication or telepresence. Our main focus has been the development of Multipath RTP (MPRTP). MPRTP is used at the endpoint for fault tolerance and aggregating capacity, but also used by the conferencing servers for media processing, i.e., transcoding, stitching video streams from multiple participants, etc. Finally, in Information-centric Networking experimentations, we contributed to a testbed across the different partners and across different technology platforms devised by different research projects (such as NetInf, PSIRP/PURSUIT, CCN/NDN).

PRECIOUS

PRECIOUS aims at improving motivation using a combination of motivational interview and gamification principles, as well as, creating a personalized system that adapts to the users' goals and preferences. The system will collect information about the user from a variety of devices and applications (sensors) that measure food intake, physical activity, stress levels and sleep patterns. Links between these key lifestyle

aspects will also be important in delivering an overall picture of the users' health status. Furthermore, the system and its sensors should be user-friendly and reduce the burden of recording where possible.

PDP - Picking Digital Pockets

In PDP, we carry out basic research in the field of opportunistic and mobile communications. The main objectives are to gain an understanding on the feasibility of data mining in mobile devices, characterizing the mutual dependencies of accuracy, latency, and convergence of views as a function of content dynamics and volume, node mobility, and cost. To this end, we develop and study related Markov and percolation models, and also study more realistic simulation scenarios. Eventually, this work provides a basis for novel algorithms and applications that exploit awareness of their (immediate) surroundings and opportunistic communication between mobile devices. The results have been published in scientific journals and conferences. PDP is a joint-research project with University of Helsinki that started in September 2012, and it is funded by the Academy of Finland. See http://www.netlab.tkk.fi/tutkimus/pdp/.

LEONE

Leone (EC FP7) develops infrastructure for 24/7 Internet measurements from an end user perspective. Leone probes are deployed in users' homes and carry out manifold active measurements of network characteristics (from low level performance metrics to quality of experience of certain applications to validating the feasibility of introducing new protocol features), which they report to per-ISP databases. Measurements are carried out towards multiple measurement servers. Leone also develops an inter-ISP protocol that allows (selective) sharing of measurement results for troubleshooting and tools for visualization and root cause analysis. Our focus is on tests for assessing the quality of experience for multimedia streaming and conferencing and for web access.

NETRADAR

Netradar is a crowd sourced mobile network measurement service. It has mobile applications for all modern mobile platforms, including Android, BlackBerry, iOS, Jolla/Sailfish, Meego, Nokia X, Symbian Belle, and Windows Phone. It was launched in Finland in summer 2012, and globally in March 2013. There are over three million measurements from mobile networks around the world, both cellular and WiFi, and over 3500 different mobile device models in the data base. Aalto researchers use the data base for various scientific projects related to mobile communication and devices. The web site is at www.netradar.org.

EIT ICT Labs SDN Activity

We participated in the EIT ICT Labs innovation activity on Software Defined Networking (SDN). The activity provides complementary funding for work that is done in Carrier Projects such as MEVICO and others. The purpose is to promote research results to practical adoption through exploration, joint experiments and other actions helping the deployments of the innovations.

CORE GROUP

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Professor Jukka Manner

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NETWORK ECONOMICS

The goal of the network economics group is to improve understanding of (mobile) technology acceptance by measuring and analyzing user behavior, by studying alternative technical and industry architectures, and by evaluating the techno-economic performance of new technologies.

RESEARCH CHALLENGES

Quantitative analysis of mobile user behavior

The always-on and multipurpose nature of personal mobile devices has enabled accurate quantitative analysis of mobile user behavior. We are challenging the boundaries of complex data mining and privacy by collecting and analyzing e.g. transaction data (from mobile devices), traffic data (from routers) and demographics data (from service providers and user questionnaires). The aim is to better understand user behavior in contexts (e.g. by location and activity), social networks (virtual vs. real world) and service adoption/diffusion.

Optimal industry and technical architecture for flexible radio access

Wireless Internet access technologies are gradually enabling more flexible use of spectrum (e.g. cognitive radio) and potentially higher utilization levels of scarce spectrum. This flexibility is emerging via two separate evolution paths: licensed and unlicensed. Our challenge is to better understand the technical, regulatory and economic rules needed to optimize the use of the bottleneck radio spectrum.

Techno-economic bottlenecks of Internet scalability

The Internet architecture and protocols need to scale up radically in the coming years due to traffic increase (video, Internet of Things, etc). Anticipation of the key architectural bottlenecks early enough is of importance. Some of these bottlenecks are techno-economic by nature and cannot be easily solved without understanding of the related economics. Our challenge is to identify these techno-economic bottlenecks and to help solving them either by designing techno-economic solutions or by cooperating with relevant technology experts.

EXAMPLE PROJECTS

MoMIE (Modeling of Mobile Internet Ecosystem)

MoMIE (2011-2013) is a national project involving the key actors of the Finnish mobile market. Mobile usage data has been collected and analyzed in a bottom-up manner to identify the trends and patterns in the Finnish market. Theories, models and hypotheses are created in a top-down manner and linked back to the experimental usage data. The resulting increased visibility to service adoption and diffusion may help market actors in business planning.

EECRT (End-to-end Cognitive Radio Testbed)

EECRT (2011-2014) includes our techno-economic analysis part to support alignment of technical architectures with market architectures. We use system dynamics, agent-based modeling, Bayes networks for the top-down and bottom-up analysis of the radio access evolution. One major observation is that local area application of white space looks more attractive.

SIGMONA (SDN Concept in Generalized Mobile Network Architectures)

SIGMONA (2012-2015) is a large EU Celtic project where our role is the techno-economic analysis of SDN and caching architectures and value networks. We use scenario planning and techno-economic modeling to analyze the feasibility of alternative architectures.

CORE GROUP

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M.Sc. Tapio Soikkeli

M.Sc. Arturo Basaure

INFORMATION THEORY

The goal of the information theory group is to solve problems in discrete mathematics that arise in coding and information theory. A variety of computational methods are used, enhanced by algebraic and combinatorial techniques. The research is mainly funded by the Academy of Finland and led by Professor Patric Östergård.

COMPUTATIONAL METHODS IN DISCRETE MATHEMATICS AND INFORMATION THEORY

The aim of the research is the study of existence and classification problems in discrete mathematics and information theory using computational methods, enhanced by algebraic and combinatorial techniques. The methods are developed in a general framework, and have been applied to numerous types of discrete structures, such as codes, designs, and graphs, just to mention a few.

One major breakthrough is the discovery of nontrivial q-analogs of Steiner systems. Several famous people have studied this problem during the last four decades, with no success, and it was then thought that maybe such structures do not exist. The interest in the problem was further increased when it turned out that such structures have applications in network coding. Joint work with teams from Germany, Israel, and USA led to the discovery of q-Steiner triple systems of order 13 in the end of 2012.

The research team has further studied and published results on difference matrices and several types of generalized Hadamard matrices; unrestricted and constant weight error-correcting codes; Hamiltonian cycles and paths in graphs; Euclidean packing and covering problems; and coloring and domination problems for graphs. Just to mention one specific result, a new record (40) for the smallest possible order of a planar hypohamiltonian graph has been obtained. All these problems concern fundamental mathematical structures or properties motivated by applications in telecommunications or more generally in engineering.

The work on classifying and enumerating discrete structures has formed a continuation of earlier work that is described in the monograph [P. Kaski and P.R.J. Östergård, Classification Algorithms for Codes and Designs, Springer, Berlin, 2006]. Along this line, we have achieved several groundbreaking results in the recent years, including a classification of the perfect binary one-error-correcting codes of length 15 and an enumeration of the Latin squares of order 11.

Switching is a general technique for transforming a discrete structure into another with the same main parameters. There are many applications for switching, for example, switching can be used to obtain new (nonisomorphic/inequivalent/...) structures from known ones. One result of the research carried out in the team is that the multitude of certain discrete structures can be explained by the fact that they are all (or almost all) connected via a sequence of switches.

Many of the computational results obtained have required very CPU-intensive computations, some of which have been distributed over extensive computer networks. For this purpose, an 80-core computer cluster was acquired in 2010 and was extended by a 256-core cluster in 2013.

Software libraries for solving various common combinatorial problems have been developed along the years. The program libexact solves instances of the so-called exact cover problem. This piece of software is frequently useful in the study of combinatorial structures, and forms an important complement to the Cliquer routines, also released by the team. The libexact and Cliquer routines were invaluable building blocks in the algorithms used to obtain several of the particular results listed above. Algorithms have further been developed in the framework of Russian doll search. Stochastic methods - in particular, tabu search - have also been considered for certain construction problems. Other types of algorithms that have been studied include approximation algorithms.

Researcher training plays a central role in the team and all doctoral students in the research team are about to defend their theses within the next couple of years. The team is collaborating extensively and internationally. The work of the team has received international recognition and the team leader was conferred the degree of "Doctor et Professor Honoris Causa" by the University of Pécs in 2013. He is also a co-Editor-in-Chief for the Journal of Combinatorial Designs.

CORE GROUP

Prof. Patric Östergård

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M. Sc. Simon Crevals

M.Sc. Ashik Kitzhakkepallathu

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M.Sc. Ville Pettersson

M.Sc. Janne Kokkala

PERFORMANCE ANALYSIS

Performance analysis group focuses on the mathematical modeling, performance analysis and optimization of modern communications systems and networks from the traffic point of view. The mathematical methods applied include stochastic modeling, queueing theory, and teletraffic theory. In addition, scheduling theory, optimization theory, discrete-event simulation, and various numerical methods play a central role. We strive both for new theoretical breakthroughs in the area of queueing and teletraffic theory and an insightful analysis of modern communications systems, networks, and applications.

RESEARCH CHALLENGES

The work done by the group is challenged by a multidisciplinary race after ever increasing technological complexity of communications systems as well as methodological innovations in related applied mathematics. The focus areas are as follows:

Optimal control of queueing systems

Along with new applications from modern computer and communications systems, scheduling theory has been revived in recent years. The group has found new fundamental results for age and size-based scheduling in the classical M/G/1 queueing context and beyond (e.g. related to opportunistic scheduling). The group has also participated in the development of near-optimal size-aware dispatching policies for parallel queueing systems typical to e.g. data centers and other server farms. Even more important in such systems is to consider the trade-off between performance and energy efficiency, which is a new line of research for the group.

Performance analysis of elastic data traffic

Bandwidth sharing networks are used to model the performance of data networks loaded with elastic traffic. The group has contributed to the extension of the concept of Balanced Fairness, which allows analytical studies of bandwidth sharing networks at the flow level. In recent years, the group has developed and analyzed various flow level models for elastic data traffic in the context of heterogeneous wireless networks.

Capacity of wireless multi-hop networks

The fundamental capacity limits of wireless multi-hop networks can be elegantly analyzed in the limit of massively dense networks. The capacity maximization separates into two distinct problems: routing at the global scale and forwarding at the local scale. For the optimal routing problem innovative applications of concepts from physics have been applied. Multiple computational methods have been developed to analyze and estimate the multidirectional forwarding capacity.

Traffic aspects of IoT

The number of devices which connect to the Internet is exponentially increasing with the emergence of Internet of Things. It generates a new traffic type, machine-to-machine communication, characterized by a huge number of potential sources but with small actual data, the analysis, modeling and optimization of which poses entirely new challenges for the performance analysis community.

PROJECTS

TOP-Energy (Towards Optimal Performance-Energy Trade-off in Server Farms)

The group is responsible for the national TOP-Energy project (2013-2017) funded by Academy of Finland. In this project, we develop advanced multi-server queueing models for server farms that include features essential for characterizing scheduling performance as well as energy efficiency. Our final target is to find optimal (or at least near optimal and robust) solutions both for the performance optimization and for the performance-energy tradeoff optimization of server farms. In the first year, we have focused on the analysis of performance-energy tradeoff in a single server models as well as the size- and energy-aware optimal dispatching problems in parallel queueing systems.

HEWINETS (Dynamic Heterogeneous Wireless Access Networks)

The group is also responsible for the national HEWINETS project (2011-2013) funded by TEKES and industry. This is a joint project with the COMNET research groups of Prof. Jyri Hämäläinen, Prof. Riku Jäntti, and Prof. Olav Tirkkonen. The focus of the project is to analyze the key issues affecting the radio resource management of heterogeneous wireless access networks relevant in LTE systems and beyond. In the third year, our focus has been on the fundamental capacity limits of multi-hop wireless networks and on the load balancing of elastic data traffic in heterogeneous networks.

ICT SHOK IoT (Internet of Things)

The group participates in the Internet of Things Programme (2012-2015) of TIVIT. In the first two years, our focus has been on the mathematical modeling and performance analysis of the initial random access procedure in LTE motivated by the potential huge signaling load of the machine-to-machine (M2M) traffic in future networks. The work has been carried out in a close collaboration with researchers in Ericsson Nomadic Lab.

CORE GROUP

Prof. (pro tem) Samuli Aalto, group leader

Prof. (emeritus) Jorma Virtamo

Dr. Pasi Lassila

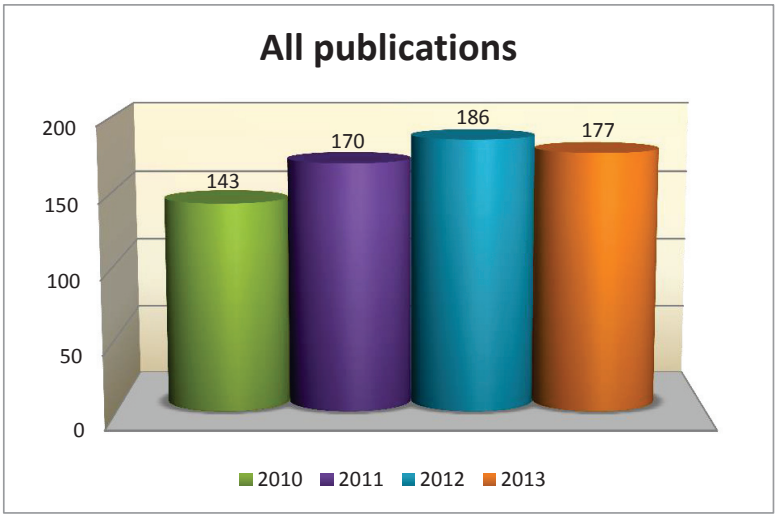
Dr. Esa Hyytiä (partly)

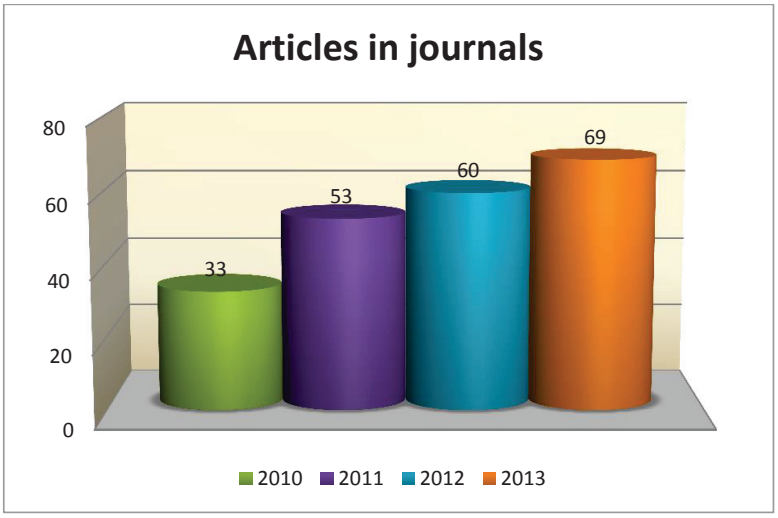
M.Sc. Jarno Nousiainen

M.Sc. Prajwal Osti

APPENDICES

PUBLICATIONS





ABSTRACTS OF DOCTORAL THESES 2013

Bulakci, Ömer:
Backhaul Link Enhancement and Radio Resource Management for Relay Deployments
Supervisor: Prof. Jyri Hämäläinen

Mobile networks are experiencing a dramatic increase in the data traffic. Besides, a continuously growing number of users expect mobile broadband access with the utmost in quality and ubiquitous connectivity. In this regard, multi-hop decode-and-forward relaying is a promising enhancement to existing radio access networks to fulfill the challenging requirements in a cost-efficient way and, thus, is an integral part of the Fourth Generation (4G) standards. Nevertheless, in order to fully exploit the potential benefits of relay deployments, proper radio resource management (RRM) is necessary.

The research in this thesis has contributed to cellular relay deployments for future mobile networks. Concretely, we have developed key RRM concepts with a particular focus on the uplink (UL) system performance to complement the existing literature. We have demonstrated the performance of these concepts by taking Third Generation Partnership Project (3GPP) Long-Term Evolution (LTE) Release 10 and beyond (LTE-Advanced) Type 1 inband relaying as a practical framework, and by considering urban and suburban scenarios. First, by performing relay site planning (RSP) we aim at improving the quality of the wireless backhaul which is crucial for the end-to-end user performance. Then, we analyze UL power control (PC) and verify its importance and applicability in relay deployments. In this context, we propose manual and automated optimizations to tune PC parameters on all links to further enhance the system performance. Moreover, we study the energy efficiency by taking into account throughput (TP) per power consumption. Further, we investigate various resource sharing strategies among and within the links. Via proposed approaches, performance enhancement is targeted along with higher system fairness and more flexible resource allocation. In addition, we address a key issue regarding the small coverage area of an RN cell in the overlaying macrocell, which results in load imbalances, inefficient resource utilization, and increased UL inter-cell interference. Specifically, we apply practical cell range extension (CRE) techniques to cope with these drawbacks.

Performance evaluations reveal that relay deployments clearly outperform macrocell-only deployments in terms of TP as well as TP per power consumption provided that proper RRM is performed. Our results also verify that the use of RSP yields substantial improvements. Furthermore, our results show that the proposed RRM concepts and the associated joint optimization strategies can fulfill the aforementioned goals while achieving significant system performance enhancements.

Casey, Thomas R.:
Evolution of wireless access provisioning: Understanding and managing value system structures and dynamics
Supervisor: Prof. Heikki Hämmäinen

The value system around wireless access provisioning consists of a large group of collaborating and competing economic actors, and a complex set of business roles and technical components, where the interactions of parts may cause the emergence of important behavior that we might not be able to see when looking at the parts separately. This thesis examines the evolution of wireless access provisioning by

studying the underlying structures and dynamics of the surrounding value system. The thesis takes a systems thinking approach to the problem where one tries to find explanation to complex phenomena by examining the linkages and interactions of elements of a system rather than the individual details, and studies the historical evolution of GSM and Wi-Fi technology tracks and future evolution towards intelligent wireless local area access points and flexible spectrum use.

A two stage approach is used where the focus is first put on value system structures in terms of generic scenarios, concurrent modeling of technical and business architectures of the value system and high level forces driving the structure. The second stage of the research models the value system dynamics caused by endogenous feedback structure and interactions between the economic actors and technical components.

The results of this thesis show how the value system around wireless access provisioning has evolved until now and how it could evolve in the future. The thesis also enhances existing and develops new methods and frameworks for modeling and understanding the structures and dynamics of value systems.

Overall the results of the thesis highlight the importance of understanding dynamic complexity in the management of wireless access provisioning. The results stress the importance of understanding the overall feedback structure of the value system and support the notion that more research is needed to understand dynamic complexity and endogenous feedback structure around wireless access provisioning and ICT services in general.

Karikoski, Juuso:
Empirical analysis of mobile interpersonal communication service usage
Supervisor: Prof. Heikki Hämmäinen

The ways in which people communicate and keep in touch with each other are changing. Our relationships are shaped by the wide variety of communication possibilities available, and the overall increase in mediated communication. On the other hand, the relationships also shape the use of different means of communication. Since the proliferation of mobile phones, mobile voice calls and SMSs have become the world's most ubiquitous form of mediated communication. More recently also newer mobile communication services have emerged, which are not necessarily provided by mobile operators, but based on the Internet instead. The merger of the mobile and Internet domains is further accelerating the changes in how we socialize.

The purpose of this thesis is to empirically analyze the use of mobile interpersonal communication services by using a quantitatively driven mixed method design, with handset-based measurements as the core data collection method. The aim is to fill in the research gap of sparse objective user-level research on mobile communication service usage. Handset-based measurements enable collecting actual mobile phone usage data from users who have opted in to participate and install a research application to their devices. Because of the personal and social "always on" nature of the data collection device, we are able to collect rich location-based and context-sensitive data about how mobile communication services are used. The main data analyzed are collected from up to 200 participants from a longitudinal research panel with a span of more than a year. In addition to handset-based measurements, surveys and semi-structured interviews are used as complementary methods.

In this thesis mobile communication services are found to be used differently based on a number of factors. Mobile phone use context and the strength of the tie between the persons communicating are the most salient ones. For example, SMSs are used more with strong ties when compared to voice calls. Moreover, the lengthiest and the briefest voice calls are made in the Home and Office contexts, respectively. Consequently, the usage interrelationships of mobile communication services are discussed from a mobile

operator perspective. The use of multiple and dynamic datasets in social network analysis is also encouraged, as the analysis of different communication channels may or may not lead to different views of the social network under analysis. Thus, the thesis and the results of the research can be valuable for practitioners and academics in the area of mobile ecosystems, particularly mobile operators. The thesis also contributes to the emerging fields of communication and social network research, namely computational social science and social computing.

Koufos, Konstantinos:
Spectrum access in white spaces using spectrum sensing and geolocation databases
Supervisor: Prof. Riku Jäntti

A spectrum license grants users the right to transmit on a particular piece of spectrum. Historically, a spectrum license has been allocated for a particular technology. While this strategy facilitates interference control, it also results in spectrum scarcity as more spectrum-efficient technologies are invented. In order to meet the increasing data traffic demands in a timely manner, a shared use of the spectrum seems to be the only viable solution. According to this line of thinking, different technologies with possibly different deployment densities can share the same spectrum under certain conditions. While shared spectrum access improves spectral efficiency, it also increases the risk for harmful interference among the different systems. This calls for a change in the traditional way of issuing spectrum licenses: instead of specifying transmit power levels, the spectrum usage rights specify the generated interference that is permitted.

Spectrum access to white spaces would enhance spectrum utilisation, while also testing the approach of controlling the interference between different systems directly rather than through the transmission power. The amount of interference generated to the license holder can be controlled by spectrum sensing and/or geolocation database access.

Interference control using spectrum sensing usually boils down to a signal detection problem. In this thesis, we show that the traditional signal detection framework is not appropriate for recovering transmission opportunities in the spatial domain and propose an alternative model. Also, sensing strategies for energy efficient wideband spectrum sensing and trade-off analysis between the service requirement and the demand in the measured spectrum are demonstrated.

At this moment, spectrum access to white spaces is mostly possible via geolocation databases. The database is responsible for handling spectrum access requests while complying with certain regulatory conditions. In this thesis, we suggest some interference control and power allocation algorithms that may govern the operation of the database. The algorithms have a low complexity to enable a real-time operation in the database. They involve simple models to capture the impact of the non-uniform demand density, terrain-based propagation and fading correlations on the generated interference. Also, we propose a joint rate and power allocation algorithm that protects the license holder in all cases.

Matuszewski, Marcin:
Business and technical aspects of mobile peer-to-peer social networks
Supervisor: Prof. Raimo Kantola

Introduction of mobile high-capacity networks, as well as the widespread penetration of powerful mobile handsets provide a good basis for the development of peer-to-peer applications in the mobile

environment. However, it is not certain if the P2P services that were well adopted in the fixed In-ternet can also be successfully launched in the mobile environment.

This article dissertation presents research results of mobile community service provisioning using P2P technology. The study was carried out on two levels: technical and business. On the business level the dissertation discusses the mobile P2P service provisioning ecosystem including analysis of stakeholder needs as well as potential scenarios for mobile P2P services. The dissertation presents the results of a user survey and a literature study. The presented material reveals that there is room for P2P services in the mobile environment, however user requirements are different than in the fixed environment. The dissertation also presents a scenario planning methodology that proposes the Schoemaker's variant of scenario planning as a suitable method for evaluating emerging mobile services. Consistent and coherent learning scenarios that were developed using the proposed methodology are also presented.

On the technical level, the dissertation presents P2P system architectures, protocols, and algorithms that enable the provision of community services in the mobile environment. In particular, the dissertation describes the world first resource sharing system that works on top of SIP networks. The system enables mobile phone users to share resources with each other and does not require any changes to the basic SIP infrastructure. A Social DHT architecture that allows for efficient formation of mobile communities is also presented. The dissertation shows how the P2P infrastructure can become a feasible cost efficient replacement for a mobile infrastructure by presenting a Distributed IP Multimedia Subsystem as well as a pioneering new mobile P2PSIP system for real-time communication services. The dissertation discusses an implementation of a P2P system that allows mobile phone users to search for knowledge in their trusted social communities overcoming the problems identified in the business study of the dissertation. The results of measurements and trials conducted show the technical feasibility of mobile community service provisioning using P2P technology.

Mäenpää, Jouni:
Framework Architecture for Decentralized Communications
Supervisor: Prof. Raimo Kantola

Peer-to-Peer (P2P) systems represent a paradigm shift from the traditional client/server architecture. Over the past decade, P2P technologies have proven themselves as a viable option for providing services in the Internet. This success has resulted in initiatives to develop standards-based P2P protocols and services. One of the major initiatives in this area is Peer-to-Peer Session Initiation Protocol (P2PSIP), a suite of communication protocols that enable the Session Initiation Protocol (SIP) to decentralize its functions. P2PSIP is being standardized in the Internet Engineering Task Force (IETF). This dissertation presents a framework architecture for decentralized communications that is built around P2PSIP and the set of technologies it uses, including the REsource LOcation And Discovery (RELOAD) P2P signaling protocol, Chord Distributed Hash Table (DHT) algorithm, and the Interactive Connectivity Establishment (ICE) Network Address Translator (NAT) traversal solution.

The framework presented in this dissertation is a set of reusable and modular software components that can be used in a flexible manner either individually or in different combinations to support the needs of a broad set of applications and use cases. Due to its flexibility and modularity, the framework is not an integrated architecture, tightly coupled set of components, or a purpose-built software platform whose components cannot function individually or are not interchangeable. The framework and all of its components were implemented as a part of the work on this dissertation.

In the dissertation, the performance of the implementation of the framework and its components is evaluated using real-world prototypes and simulators. The focus is on evaluating the performance of DHT

maintenance routines, ICE-based NAT traversal, the operations the framework provides to applications, and the performance of the implementation of the framework in mobile environments. Based on the performance analysis, missing features and performance bottlenecks are identified. The performance bottlenecks are addressed and the missing features are added by designing new components to complete the framework. These components include self-tuning, service discovery, M2M communication, and session setup delay optimization components.

The contributions of this dissertation can be divided into three categories. First, the delays associated with using the services and operations provided by the framework are analyzed and optimized. Second, the overlay network platform that the framework provides is evaluated and extended. Finally, the framework is applied to new use cases. The overall result of the work is a framework architecture for decentralized communications that is scalable, adaptive, generic, modular, based on emerging standards, and has high performance.

Nousiainen, Jarno:
Forwarding Capacity in Large Wireless Multihop Networks - A Computational Approach
Supervisor: Prof. Samuli Aalto

Wireless multihop networks are networks without any fixed infrastructure. This thesis concentrates on a network consisting of a plethora of immobile nodes communicating with each other over a shared wireless channel. The intrinsic nature of the shared wireless channel makes it difficult to efficiently avoid interference between the transmissions, and the exact capacity of such a network is in many respects an open question.

At first, we characterize the capacity problem in a massively dense wireless network where a separation of scales emerges, and the problem can be separated into two different subproblems. The two subproblems loosely correspond to routing at the global scale and forwarding at the local scale. We focus on the latter one and study the microscopic level multidirectional forwarding capacity problem that considers an infinitely large network's capability to relay information. Because of the complexity of analyzing a large random network and wireless interference, the main approach is to construct algorithms that produce numerical bounds or estimates for the forwarding capacity, and simulate them for large network realizations.

The methods used for studying the forwarding capacity are presented in two parts. The first part considers the instantaneous forwarding capacity. The instantaneous forwarding capacity can be achieved temporarily but cannot be maintained for a longer time period. It is a natural upper bound for the actual forwarding capacity and can be analyzed with more complex ways of modeling interference, such as the SINR-based models, in addition to the simple Boolean interference model.

The actual forwarding capacity with multihop traffic under the Boolean interference model is considered in the second part. In this part, the upper bound provided by the instantaneous capacity is tightened for a small number of neighbor nodes, where it is less accurate. We also provide a lower bound that shows a notable improvement compared with previous results for uncoordinated opportunistic forwarding. Finally, an estimate is found for the forwarding capacity. The dependence of the estimate on the directional distribution of the traffic is studied to determine the possible gain from interleaving traffic in different directions compared with time sharing between the directions. Eventually, it is illustrated how the results for the forwarding capacity can be used with the macroscopic level results to obtain the total capacity of a large wireless network. The thesis hence makes it possible to calculate a numerical estimate for the total capacity.

Wei, Lu:
Towards Robust Spectrum Sensing in Cognitive Radio Networks
Supervisor: Prof. Olav Tirkkonen

This thesis focuses on multi-antenna assisted energy based spectrum sensing. The studies leading to this thesis have been motivated by some practical issues with energy based detection. These include the noise uncertainty problem at the secondary receiver, the presence of multiple active primary users in cognitive cellular networks, the existence of unknown noise correlations and detection in the low signal-to-noise ratio regime.

In this thesis, the aim is to incorporating these practical concerns into the design of spectrum sensing algorithms. To this end, we propose the use of various detectors that are suitable for different scenarios. We consider detectors derived from decision-theoretical criteriors as well as heuristic detectors. We analyze the performance of the proposed detectors by deriving their false alarm probability, detection probability and receiver operating characteristic. The main contribution of this thesis consists of the derived closed-form performance metrics. These results are obtained by utilizing tools from multivariate analysis, moment based approximations, Mellin transforms, and random matrix theory.

Numerical results show that the proposed detectors have indeed resolved the concerns raised by the above practical issues. Some detectors could meet the needs of one of the practical challenges, while others are shown to be robust when several practical issues are taken into account. The use of detectors constructed with decision-theoretical considerations over the heuristically proposed ones is justified as well.

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Interference canceling power control games in Gaussian interference channels.
IEEE International Symposium on Information Theory, ISIT 2013, Istanbul, Turkey, July 7-12, 2013. pp.1112-116.
Electronic publication http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6620399

THESES 2013

Author: Topic	**Supervisor**
Abelló Lozano, Albert: Performance Analysis of Topologies for Web-based Real-time Communication (WebRTC)	Jörg Ott
Alam, Ahmad Mahbubul: Hybrid Propagation Models Applied in TV White Space Database Construction	Jyri Hämäläinen
Ali, Majid: Public e-Procurement Interoperability in the EU (Case Study)	Jörg Ott
Arminen, Lauri: Saumaton leimakytkentä operaattorin verkossa	Raimo Kantola
Bayyana, Sri Dutt: Understanding Smartphone Usage Dependency	Kalevi Kilkki
Butta, Yonas Abebe: Building of Trust by Using Deep Packet Inspection Technology	Raimo Kantola
Cakmak, Görkem: Internet Interconnection Ecosystem in Finland	Heikki Hämmäinen
Chen, Xi: Automated Testing for Mobility Management Entity of Long Term Evolution System	Jyri Hämäläinen
Chen, Yiye: Coordinated Multipoint Communication in Heterogeneous Networks	Jyri Hämäläinen
Demirbilek, Özkan: Comparative Analysis of Spectrum Policy and Mobile Market Structure	Heikki Hämmäinen

Desta, Michael Solomon: A Local Pedestrian Mobility Model for Urban Content Sharing	Jörg Ott
Dhungana, Saurav: Mobile Web Usage: A Network Perspective	Heikki Hämmäinen
Eldishnawy, Mohamed: Adapting Open Innovation in Information and Communications Technology Ecosystem Dynamics	Kalevi Kilkki
Hakkarainen, Simo: Expectations and User Experiences as Determinants of Technology Adoption and Continued Use	Kalevi Kilkki
Hassan, Syeda Sarita: Performance and Challenges of Coordinated Multipoint Transmission and Reception in Heterogeneous Network	Jyri Hämäläinen
Holmström, Jasmine: Techno-Economic Model for Broadband Copper Access Life-Cycle	Heikki Hämmäinen
Huang, Yi: Outdoor Signal Strength Measurement at TV Band and ISM Band in Otaniemi Campus	Riku Jäntti
Häkkinen, Petteri: Suunnitteluratkaisujen tuottaminen ja arviointi nosturin huoltokäyttöliittymässä	Timo Korhonen
Jacquot, Vincent: Test Bed for Multipath TCP	Jukka Manner
Kainulainen, Matias: Laajakaistan tilaus-toimitusprosessin automatisointi osoitteenmuutosten ja tekniikanvaihtojen tapauksissa	Jukka Manner
Kalliomäki, Antti: Koostepalvelujen transaktionhallinta	Jukka Manner
Karaiskos, Christos: Altruistic Transit Beamforming for Cross-Layer Interference Mitigation in Heterogeneous Networks	Jyri Hämäläinen
Kataja, Jere: Ethernet-siirtotekniikoiden vertailu	Raimo Kantola
Kaushik Ganesan, Vishnu Prasad: Network Time Synchronization in Time Division – LTE Systems	Olav Tirkkonen
Kotiranta, Tuomas: Itsenäisen IP-pohjaisen radioverkon käyttö säähavaintojen siirrossa	Samuli Aalto
Kyazze, Bob: Centralized Ethernet Switching	Jukka Manner
Lagerström, Susanne: Let's go Out and Play: Designing Interactive Outdoor Games for Children	Jyri Hämäläinen
Larjomaa, Tommi: Improving Bandwidth in Wireless Mesh Networks	Patric Östergård
Maheshwari, Kapil: Core Network Design of Software Defined Radio Testbed	Pasi Lassila
Mallya, Pradeep: Effect of Feedback Delay in Cooperative Multipoint Communications	Jyri Hämäläinen

Manninen, Kalle: Management of Node Protection in Packet-Based Mobile Backhaul	Raimo Kantola
Marjamaa, Jussi: A Measurement-based Analysis of Machine-to-Machine Communications over a Cellular Network	Jyri Hämäläinen
Meriläinen, Mikko: Parametrisoinnin vaikutus toisen sukupolven maanpäällisen digitaalisen television liikkuvaan vastaanottoon	Jyri Hämäläinen
Mir, Muhammad Waqas: Perpetual Battery Life for Machine to Machine Communication Devices with Cellular Access	Jyri Hämäläinen
Morab Vishwanath, Anil: Practical Implementation of Cognitive Radio Architecture for Radio Resource Management and Control	Olav Tirkkonen
Mäntysaari, Jarkko: Migration to a New Internet Protocol in Operator Network	Raimo Kantola
Nurminen, Riikka: Automated Analysis of Base Station Reception Problems in LTE Uplink	Jyri Hämäläinen
Nyman, Mathias: Navigation Behavior Analysis and User Profiling Based on Automatically Collected Website Data	Kalevi Kilkki
Oguntoyinbo, Oludayo: The Future of LTE: The Femtocells perspective	Jyri Hämäläinen
Pahlevan, Maryam: Signaling and Policy Enforcement for Co-Operative Firewalls	Raimo Kantola
Palmgren, Aura: Osallistavan suunnittelun työkalujen tutkiminen tunnetilan avulla	Kalevi Kilkki
Parsian, Hormoz: Comparison of Asset and Atoll Cellular Planning Tools for LTE Network Planning	Jyri Hämäläinen
Puibaraud, Marine: Design of automated system for the diagnosis of the Internet connections	Jukka Manner
Rony, Rakibul Islam: Small Cells for Broadband Internet Access in Low-Income Suburban Areas in Emerging Market Environments	Jyri Hämäläinen
Shariatmadari, Hamidreza: Channel Ranking Scheme in Wireless Sensor Networks Based on Packet Delivery Ratio Estimation	Riku Jäntti
Shen, Yue: An Evalutation Platform on Trust Management for Unwanted Traffic Control	Raimo Kantola
Silander, Jon: Katsaus identiteetinhallinnan teknologioihin ja niiden tulevaisuuden näkymiin	Jukka Manner

Takala, Mikko: Tuotantokriittisen prosessiverkkoympäristön valvonta	Riku Jäntti
Tang, Qiuyang: A dynamic sheduling mechanism to improve energy efficiency in cellular networks S	Riku Jäntti
Tiilikainen, Sami: Web-sovelluksen toimintalogiikka palvelimelta käyttäjän selaimeen	Jukka Manner
Ud Din, Fawad: Mobile Internet Traffic Analysis: Session Level Approach	Heikki Hämmäinen
Wang, Yue: Scenario Analysis on Internet Consumer Privacy	Heikki Hämmäinen
Väisänen, Hanna: Yhteyskeskusjärjestelmän vaatimusmäärittely ja kilpailutus	Jukka Manner
Yu, Bin: Data Compression for Energy-Efficiency Web Access on Mobile Devices	Jukka Manner
Zhao, Xuetao: Bluetooth for Audio Transmission	Riku Jäntti

LICENTIATE OF TECHNOLOGY 2013

Author: Topic	**Supervisor**
Halinen, Turo: Distributed transmission for cooperative wirelessnetworks	Jyri Hämäläinen
Savola, Pekka: Internet-operaattoreihin kohdistetut tekijänoikeudelliset estomääräykset erityisesti vertaisverkkopalvelun osalta	Raimo Kantola

ACTIVITIES

ACADEMIC ACTIVITIES 2013

Jyri Hämäläinen

- Opponent to Carlos Héracles Morais de Lima, University of Oulu

Riku Jäntti

- Opponent to Liping Wang, KTH Royal Institute of Technology

Jörg Ott

- Opponent to Christian Dannewitz, Universität Paderborn
- Opponent to Tomas Kupka, University of Oslo

Olav Tirkkonen

- Opponent to Muhammad Naseer-ul-Islam, Technische Universität Ilmenau
- Opponent to Adrian Kotelba, University of Oulu

Patric Östergård

- Opponent to Thomas Feulner, Universität Bayreuth
- External Examiner of Doctoral Thesis, Adrian Kotelba, University of Oulu

Zheng Yan

- Opponent to Alexander Wei Yin, University of Turku
- Invited talk at the VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY (VirginiaTech), USA, Oct. 2013

CHAIRMANSHIPS AT THE CONFERENCES IN 2013

Zheng Yan

- IEEE TrustID 2013, Australia (program chair)
- Cute-2013 (vice program co-chair)
- IEEE/IFIP EUC 2013 (workshop co-chair, vice program co-chair)
- IEEE/IFIP DMIoT 2013 (program co-chair)

- DataTrust-13 (publicity co-chair)

Patric Östergård

- WCC 2013, International Workshop on Coding and Cryptography, Bergen, Norway
- Nordic Combinatorial Conference, Stockholm, Sweden

VISITS ABROAD IN 2013

Beneyam Berehanu Haile

- University of California, USA, 3 months

Timo Smura

- University of California, Berkeley, USA, 1 year

Esa Hyytiä

- McMaster University, Canada, 2 weeks

Maliha Urooj Jada

- Universitat Politècnica de Catalunya (UPC), Spain, 1 year

Renaud-Alexandre Pitaval

- Imperial College London, United Kingdom, 4 months

Zheng Yan

- Xdian University, China, 3 months

Zhong Zheng

- University of Erlangen-Nuremberg, Germany, 3 months

Alexis Dowhuszko

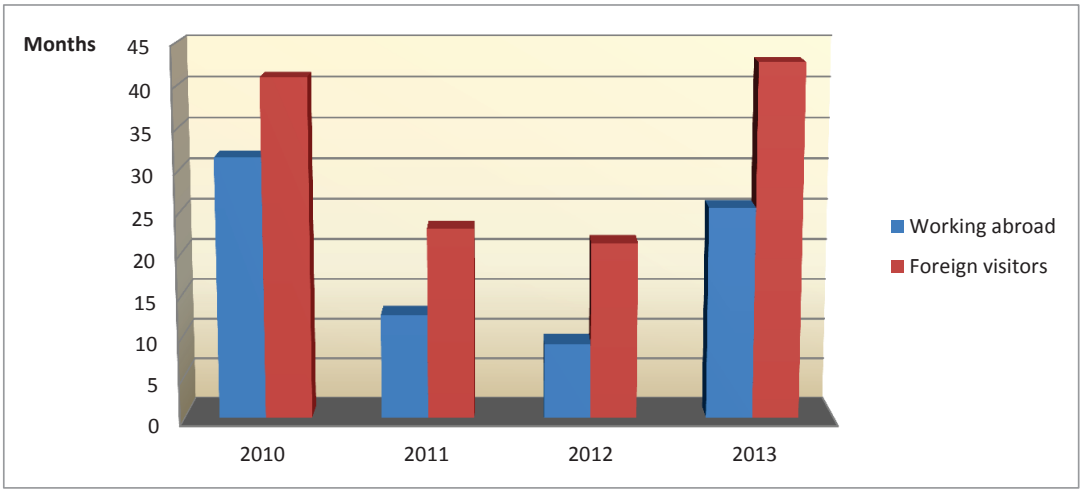
- Beijing University of Posts and Telecommunications, China, 2 weeks

Sassan Iraji

- Beijing University of Posts and Telecommunications, China, 1 week

FOREIGN VISITORS IN 2013

- Aazhang, Behnaam from Rice University, USA
- Bonald, Thomas from Télécom ParisTech, France
- Bou Saleh, Abdallah from Intel, Germany
- Bouwman, Harry from Delft University of Technology, Netherlands
- Bulakci, Ömer from NSN, Germany
- Charaf, Hassan from Budapest University of Technology and Economics, Hungary
- Charitoudi, Konstantinia from University of Glamorgan, United Kingdom
- Correia, Luis M. from Universidade Técnica de Lisboa, Portugal
- Fanti, Marco from University of Torino, Italy
- Ferrer Guasch, Vicent from University Polytechnic Catalonia, Spain
- Helmy, Ahmed from University of Florida, USA
- Hess, Andrea from University of Vienna, Austria
- Madden, Gary from Curtin University, Australia
- Pastor Figueroa, Giancarlo from Universidad Rey Juan Carlos, Spain
- Sukareviciene, Gintare from Vytautas Magnus University, Lithuania
- Taricco, Giorgio from Politecnico di Torino, Italy
- Tutschku, Kurt from Blekinge Institute of Technology, Sweden
- Uykan, Zekeriya from Dogus University, Turkey



Department of Communications and Networking

Comnet: Annual Report 2013

Sassan Iraji (Editor)

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