Department of Communications and Networking

Annual Report 2014

Ruifeng Duan (Editor)

Aalto University publication series
SCIENCE + **TECHNOLOGY** 11/2015

ANNUAL REPORT

Ruifeng Duan (Editor)

Aalto University
School of Electrical Engineering
Department of Communications and Networking

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CONTENTS

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 2014

DEPARTMENT HEAD'S REPORT

In 2014, three new professors joined Comnet: two associate professors Prof. Antti Oulasvirta and Prof. Tarik Taleb and one professor of practice Jarno Limnéll. Associate Professor Antti Oulasvirta came from Max Plack Institute of Informatics, Germany. His research area is user interfaces and his research group strengthens the communications ecosystem focus area of Comnet. Antti got very good start by obtaining the ERC starting grant for his research. Prof. Tarik Taleb come from NEC, Germany. His research area is mobile core networks, mobile cloud networking, and mobile multimedia streaming. His research work strengthens the core – future networking paradigms - research focus of Comnet. Prof Jarno Limnéll shares his time between Aalto and Inter Security. His research field is cyber security - a topic that is becoming increasingly important in our society.

Professor Jarno Limnéll and Professor Jukka Manner have ranked among the top 100 most influential experts in the ICT sector in Finland. Especially they have raised the general public's knowledge of cyber security aspects. Prof. Manner has also been active in discussions related to energy efficiency of ICT systems and quality of service offered by Mobile Operators. The Netradar application for measuring the performance of mobile networks developed by his group has drawn a lot of interest.

The year 2014 was year of test-beds. Staff scientist Dr. Jose Costa-Requena's team built SDB-based LTE enhanced Mobility Management Entity and the team led by University Lecturer Dr. Kalle Ruttik implemented TD-LTE base band processing using general purpose processors and non-real-time operation system. This is the first soft-real-time implementation of a LTE base station. Together these two platforms allow the department to do experimental mobile communication systems research. The TD-LTE platform was utilized to demonstrate network controlled direct device-to-device communications in EU FP7 METIS project.

Coment researchers also made progress in Information theory. Professor Patric Östergård's group discovered perfect MDS codes over an alphabet of size 8 that are not equivalent to Hamming codes; this was the last open case for alphabets whose size is a proper prime power.

In addition, the Comnet researchers managed to commercialize their research results: Space-time Networks Oy is commercializing the SCAMPI protocol stack developed by Comnet researchers for building infrastructure free communications in challenging environments. Nemu Dialogue Systems Oy is building a tool for monitoring and managing the performance of multimedia calls.

June 8, 2015 Riku Jäntti

ADMINISTRATION

PERSONNEL

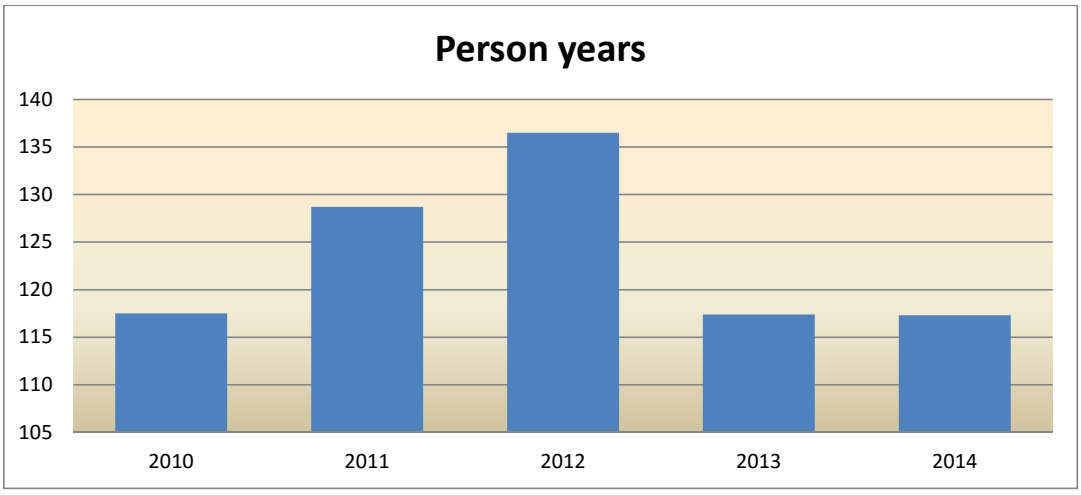


Figure 1: The Development of the person years 2010-2014

Table 1: Personnel structure

Year	2010	2011	2012	2013	2014
Professors	9	9	9	9	11
Postdocs	10	10	8	4	13
Researchers with doctoral degree	8	8	7	9	7
Doctoral students	62	62	60	56	59
Research assistants	34	34	41	29	21
Teaching personnel (incl. part-time)	4	4	4	4	5
Technical services	5	5	3	4,5	6
Administration	4,4	4,4	5,5	1*	1
Total	136,5	136,5	140	116,5	123

*Administration services are provided by the School of Electrical Engineering

PROFESSORS

Riku Jäntti
Head of Department

Patric Östergård

Jyri Hämäläinen
Deputy Head of Department
(till Sep. 2014)

Antti Oulasvirta

Heikki Hämmäinen

Raimo Kantola

Jukka Manner

Jörg Ott

Olav Tirkkonen
Deputy Head of Department
(from Oct. 2014)

Tarik Taleb

Limnéll Jarno

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 started in 2013 and was mostly competed in 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. In late 2014 also first Linux and OSX computers were moved to Aalto domain. However, many workstations 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. Thanks to reorganization and above mentioned move of basic IT support to Aalto ITS there is expected to have more time also for developing research and teaching facilities.

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 include redundant 10 Gbit/s connection by end of 2014. The upgrade proved its value by reducing impact of DDoS attacks towards some services hosted by Comnet and resiliency towards network outages. A network fully isolated from Aalto campus network 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.

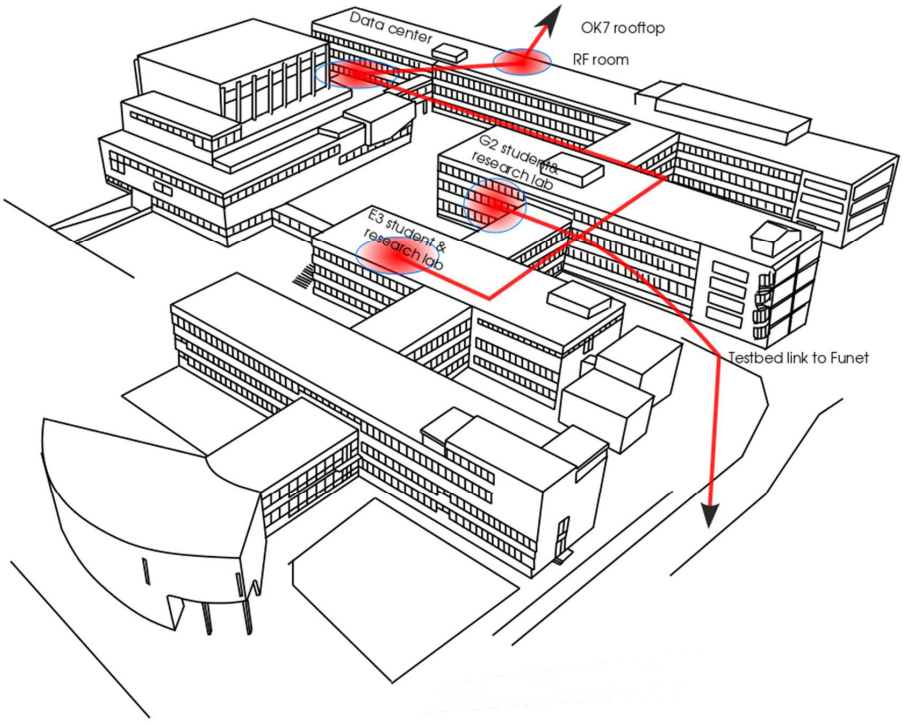


Figure 2: Department research and teaching facilities and fiber optic connections

FINANCIAL ISSUES

EXPENSES AND SOURCES OF FUNDING

Table 2: The Development of the expenses 2010-2014 (€)

Expenses (in thousands)	**2014**	**2013**	**2012**	**2011**	**2010**
Personnel	6,044	6,039	6,637	6,088	5,580
Facilities	741	586	587	583	541
Services	354	184	293	150	102
Depreciations	283	270	279	186	119
Other expenses	559	601	615	723	658
Internal expenses	726	735	1,218	1,116	393
Total expenses	**8,707**	**8,414**	**9,629**	**8,846**	**7,394**

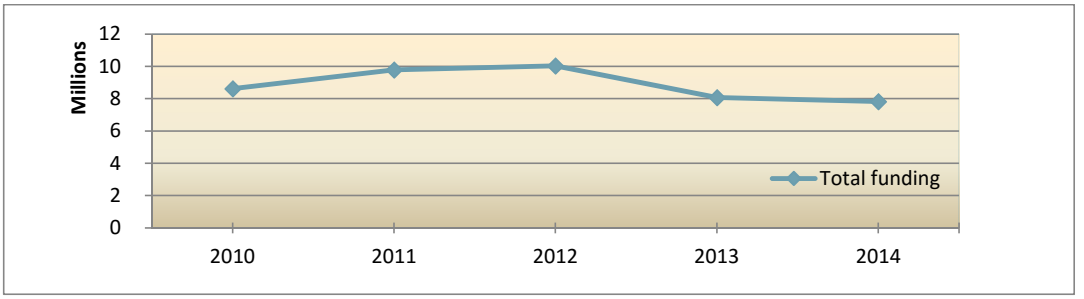


Figure 3: The Development of the total funding 2010-2014

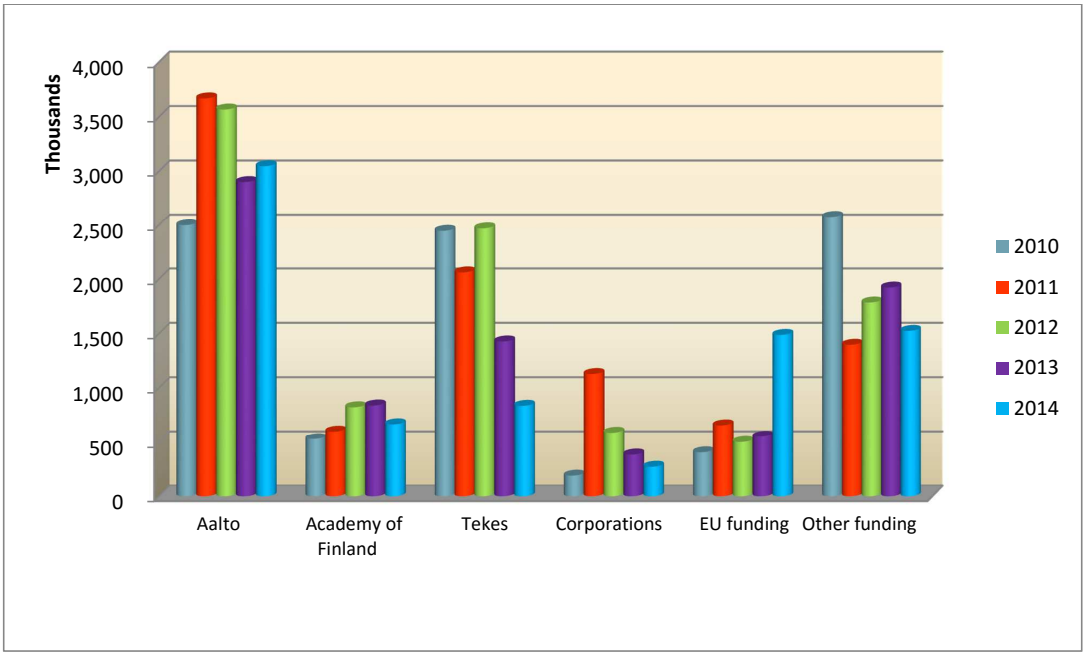


Figure 4: The Development of the funding by funding source 2010-2014

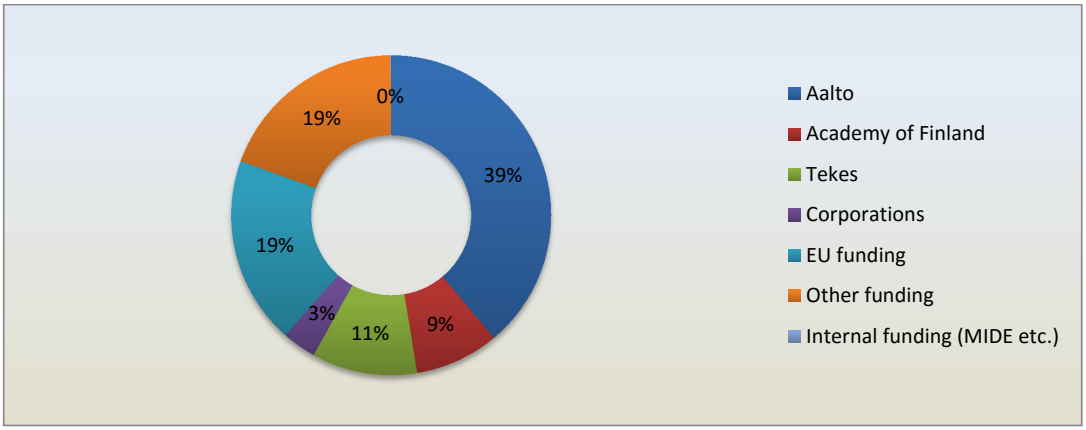


Figure 5: The sources of funding in 2014

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.

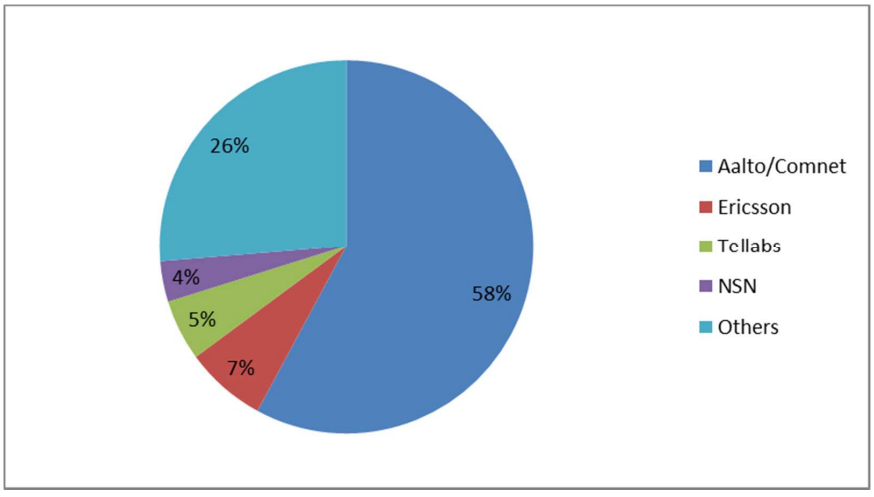


Figure 6: Employers of Master´s thesis students in 2014

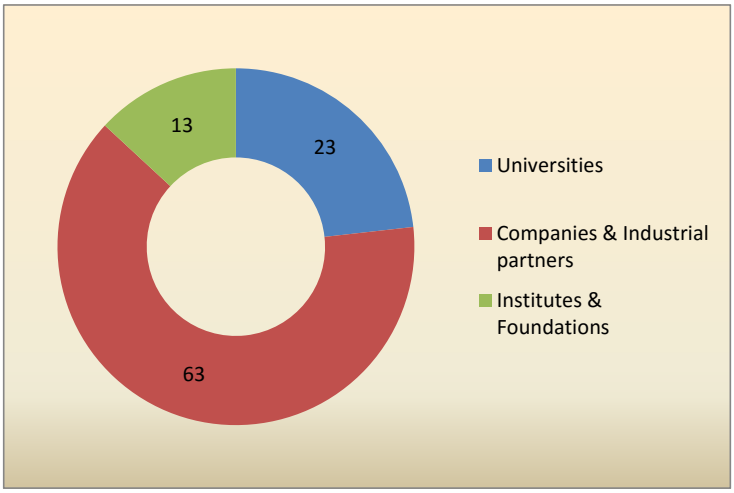


Figure 7: The cooperation – Comnet's partners in projects in 2014

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 education of Communications Engineering, which is attracting talented students from numerous countries.

The Deputy Head of Department is responsible for teaching at Comnet. Prof. Jyri Hämäläinen served as Deputy Head till the end of September 2014, when he was succeeded by Prof. Olav Tirkkonen. 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

In 2014 Comnet teaching development days were held in June and in August. Emphasis was put on the forthcoming reform of the master's level curriculum and its courses. The events were well attended and led to various concrete actions.

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.

Reflecting the ongoing master's program renewal, the number of courses taught by the department is constantly decreasing. This action ensures that core courses in the field are delivered in well-designed packages.

CURRICULUM DEVELOPMENT

The new bachelor's program in Electrical Engineering started in fall 2013. The new master's program in Computer, Communications and Information sciences will start fall 2015.

In bachelor's program Comnet is responsible of teaching C-programming, as well as Signals and Systems, to all students in the ELEC. 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, emphasizing quality in learning and teaching, and promote student mobility in Aalto. Bachelor's level courses in the new program will be lectured in Finnish and the master's level courses in English.

During 2014, development of new master's programs was ongoing in the university. The new programs will start in fall 2015.

INTERNATIONAL PROGRAMMES

In 2014, Comnet was 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 has been 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 program is currently active:

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

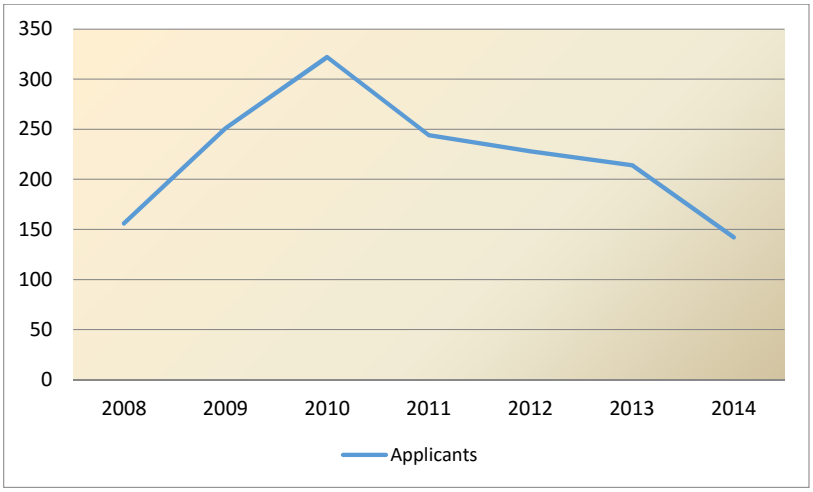


Figure 8: The number of first-choice applicants into International Master´s Programmes on Communication Engineering & Communications Ecosystem

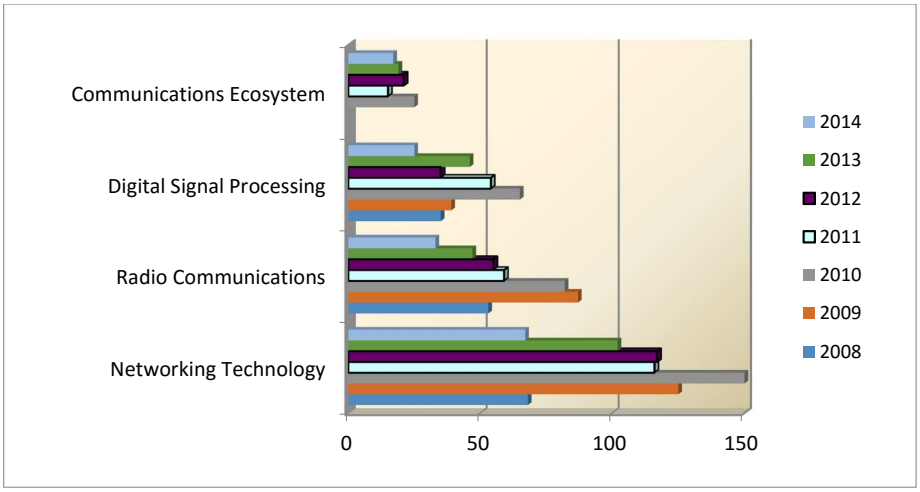


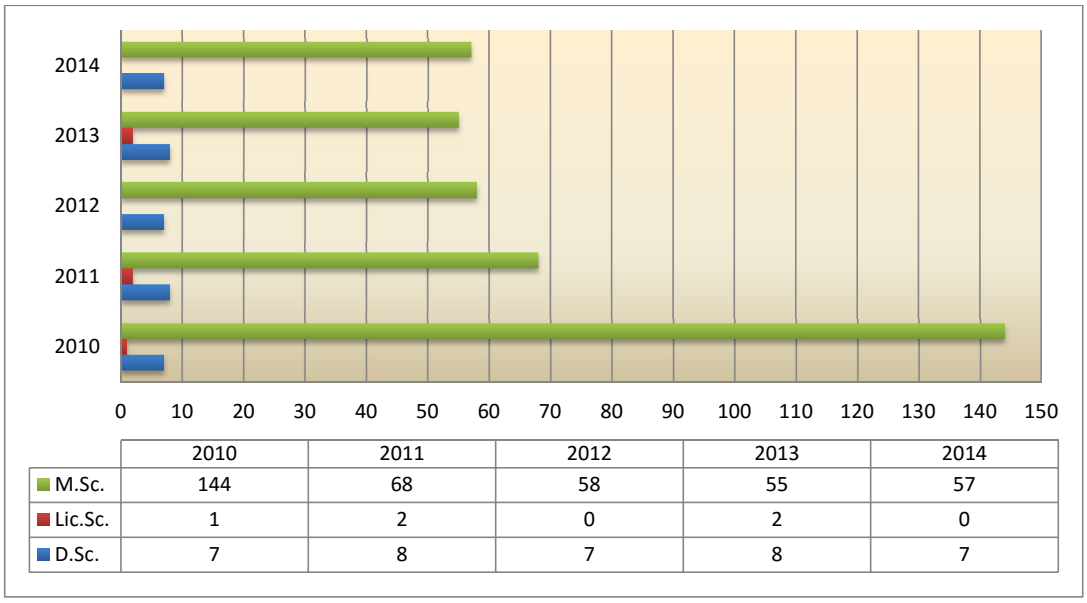
Figure 9: The number of first-choice applicants into international programmes per major.

COURSES IN 2014

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

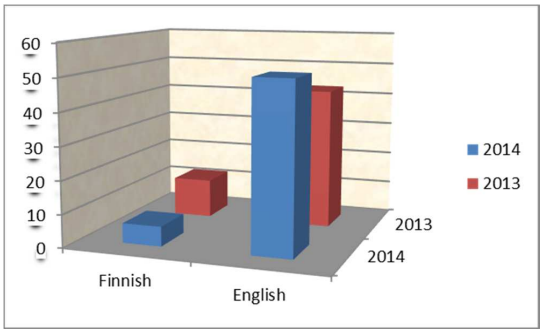
S-38.3184	Network Traffic Measurements and Analysis P
S-38.3191	Network Service Provisioning P
S-38.3194	Wireless Networks
S-38.3310	Thesis Seminar on Networking Technology
S-38.3455	Challenged Networks P
S-38.3600	UNIX Application Programming
S-38.3610	Network Programming
S-38.4043	Postgraduate Seminar 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 2014



	2010	2011	2012	2013	2014
M.Sc.	144	68	58	55	57
Lic.Sc.	1	2	0	2	0
D.Sc.	7	8	7	8	7

Figure 10: Number of degrees at Comnet in 2010-2014



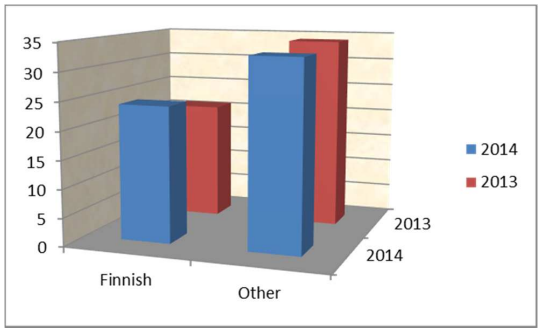


Figure 11: Languages of Master's theses 2013-2014 (left) and Nationalities of M.Sc. graduates (right)

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"). In addition, Network Security and Trust, Cloud-based Mobile Networks, and the optimization of interactive technology for human use are also conducted.

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). Five *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.
- *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.
- *Cloud-based Mobile Networks* conduct research on how to dynamically build flexible and elastic virtual mobile networks on the cloud along with their lifecycle management. It leverages ongoing advances in the areas of Network Function Virtualization, Software Defined Networking, and Mobile Edge/Fog Computing.
- *Network Security and Trust* is focused on creating new networking paradigms, protocols, algorithms and functions for a trustworthy Internet. The technology of Customer Edge Switching provides cooperative firewalls for customer networks. Such firewalls collect and attribute evidence of network attacks making a wide area network wide trust management system feasible.

With 11 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 other rising themes that will affect our research in the coming years are *cyber and network security, and cloud-based mobile networks*.

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 (LSA). 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 benefits common purpose servers can provide compared to specialized hardware. Radio access networks (RAN) require similar flexibility 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.

- **Cloud-based wireless networks:** Conducting research on how to dynamically build flexible and elastic virtual mobile networks on the cloud along with their lifecycle management. The concept of cloud-based mobile networking is expected to be part of 5G and is currently gaining lots of attention among operators, vendors, and cloud providers. It leverages ongoing advances in the areas of Network Function Virtualization, Software Defined Networking, and Mobile Edge/Fog Computing. The concept is very interesting as it represents a CAPEX/OPEX-efficient solution to many challenges operators are currently facing.

- **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 unlicensed 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.

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

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 billions 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.

Machine-to-Machine – Redefining Information Sharing and Enablers (M2MRISE): M2MRISE is part of the EIT ICT Labs action line Networking Solutions for Future Media. Ericsson AB, KTH Royal Institute of Technology, Aalto University, Nokia Research Center and Orange S.A. constitute the constellation of partners. The project fosters the development of a framework that enables services based on Machine-to-Machine (M2M) communications and Internet of Things (IoT), within current and future cellular networks, by taking into account overall system, service and business model aspects.

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.

CORE GROUP

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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 Network Security and Trust 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 Network Architecture, Protocols, and Services led by Professor Jörg Ott conducts research on networked systems and protocols with a focus on transport and application layer aspects. The current a number of core research themes are: 1) Delay-tolerant, opportunistic, and information-centric architectures to enable and sustain communications in (not just) 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, in particular, working with web-based real-time communication (WebRTC) and large-scale IPTV distribution and adaptive streaming, 3) Scalable and secure cloud infrastructure. Interests are some fundamentals of cloud-based architecture, in the short term including secure and privacy-preserving cloud operation and scalable and adaptive cloud systems. For the longer term, seeking to understand how to gain flexibility in network- and cloud-based service provisioning by rethinking the basics of networked operating systems; 4) Network measurements. The research is 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 Evolving Internet Group of Jukka Manner works on a wide range of topics related to the Internet, from mobile data communication to green ICT and cyber security, and has developed a number of technologies to enhance data transport and network connectivity of end hosts, both mobile and fixed. The group has widened its work to include a number of critical aspects related to the evolution of the Internet. The group has built an extensive data center laboratory at Aalto, to study cooling, heat energy re-use and power usage of data centers. The group has a long history with research in military and government communication infrastructures and protocols. Other research themes are 1) Ethernet-based networking extending the IETF-driven TRILL technology (also called Routing Bridges); 2) network and cyber security

with a focus on Ethernet-based networks and industrial systems and 3) 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 2014, 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 2014 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 apply 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 2014, we designed and developed a practical reputation system for content services in pervasive social networking, investigated the applicability of trust management based unwanted traffic control mechanism using game theory, developed a prototype system for distributed unwanted content control in MANET and tested its performance, developed a usable reputation and recommender prototype system for mobile apps based on trust behavior study and tested this system through 2-round of user studies. We also performed an extensive survey on trust management in Internet or Things and edited a special issue on Trust in Cyber, Physical and Social Computing, in the journal of Computers and Security.

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-preserving data mining, data access control in social networking, anonymous authentication etc. Particularly, we explored a series of cloud data access control schemes based on trust and reputation.

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.

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 2014, 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. 2014 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 2014. 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

Professors:

Professor Raimo Kantola

Professor Jukka Manner

Professor Jörg Ott

Senior Researcher

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M.Sc. Hammad Kabir

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

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

Professor Heikki Hämmäinen

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M.Sc Henna Suomi

M.Sc Nan Zhang

M.Sc. Michail Katsigiannis

M.Sc. Tapio Soikkeli

M.Sc. Arturo Basaure

INFORMATION THEORY

The information theory group studies 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.

Major breakthroughs have been made on the topic of q-analogs of designs. Such structures are of interest both in theory and practice, as a part of network coding. An earlier discovery of nontrivial q-analogs of Steiner systems has now been followed up by new results in particular regarding q-analogs of packing designs and large sets of designs. This work has been carried out jointly with scholars from the University of Bayreuth and Darmstadt University of Applied Sciences.

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. All these problems concern fundamental mathematical structures or properties motivated by applications in telecommunications or more generally in engineering. The team has also studied cryptographic aspects of channel coding in a project financed by MATINE.

Two specific results worth mentioning are the discovery of new perfect codes over an alphabet of size eight, and a new lower bound for the capacity of a cycle of length 7. The latter result is one of only a few new results during the last decade on a famous and very hard problem in information theory.

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, several new results have been obtained for various types of objects.

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 - including tabu search - have also been considered for certain construction problems.

Researcher training plays a central role in the team and at least three doctoral students in the team will be defending their theses in 2015. The team is collaborating extensively and internationally. The team has been actively participating in Cost Action IC1104: Random Network Coding and Designs over GF(q).

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 Pecs in 2013. He is also co-Editor-in-Chief for the Journal of Combinatorial Designs.

CORE GROUP

Prof. Patric Östergård

Dr. Ferenc Szöllösi

M.Sc. Simon Crevals

M.Sc. Ashik Kizhakkepallathu

M.Sc. Janne Kokkala

M.Sc. Pekka Lampio

M.Sc. Ville Pettersson

Ville Kuvaja

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.

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

USER INTERFACES

The group studies the design of user interfaces for human use. Our unique approach is to cast user interface design as an optimization problem. This approach bears many benefits. Ideal design parameters can be derived without expensive user studies. Whole interface designs can be identified in very large, multidimensional design spaces. Some methods guarantee optimal designs. Interactive design tools allow designers to delegate well-known aspects of design problems to a computer, thus reducing the amount of effort. Even novice designers are able to produce great user interfaces. By contrast, the prevailing methods of user-centered design and interaction design are expensive, depend on experience, and results vary.

The group develops algorithms, models, and interactive tools for interface optimization. The models are informed by theories in behavioral and social sciences and acquired or calibrated in rigorous experimental studies. We have demonstrated the results in a number of applications ranging from classic problems like keyboards to novel multimodal interfaces.

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:

Models of Human-Computer Interaction

A hard challenge is methodology for efficient acquisition of 1) multi-factor predictive models and 2) probability distributions describing what users do with the new UI. Moreover, the objective function must be represented in a way that is 3) rapidly executable in code yet 4) fully interpretable and editable by the designer. We aim at methodology for acquiring so-called strongly generalizing models that cover an order of magnitude more factors. The existing mathematical models in HCI tend to have less than 6 variables. Ten factors is set here as the minimum target necessary to start considering important interrelated aspects like expectations, learning, fatigue, satisfaction, or aesthetics. However, models that cover a high number of factors have been previously out of reach due to highly inefficient data collection and model identification. Second, the typical bigram-based weighing used in UI optimization trivializes user behavior, if compared to the descriptions of users and tasks in user-centered design.

User Interface Optimization

Our second challenge is to extend efficient optimization methods beyond keyboards, moreover in a way that better respects designers' requirements. For this end, we want to formally define decision problems in UI design and go beyond the QAP (quadratic assignment problem).

Our applied goal is an effective paradigm for interactive UI optimization. Our previous work on MenuOptimizer integrated a multi-scale real-time optimizer to QtDesigner. Preliminary results with novice designers were promising, suggesting improvements in efficiency and outcomes. However, much work needs to be completed to achieve a paradigm that truly accelerates the convergence of the designer—optimizer system. Interactive UI optimization must better deal with incomplete knowledge, it must better

integrate with existing tools and practices, and it must guide the designer to converge faster to better results.

PROJECTS

Quality of Experience Models for Flexible Access

To advance network management and optimization for a multi-access scenario, a key challenge is to model user experience of network quality in its typical conditions. We are running controlled experiments for modeling QoE as a response to long-term variation and sudden changes in QoS. In the experiments, users are asked to do tasks like video watching for a longer period of time, and their responses are periodically measured using standardized questionnaires. This paradigm allows covertly manipulating the QoS in a way that emulates the flexible access concept. In the baseline condition we compare against realistic conditions lacking the flexible access support. Second, we will run controlled experiments for modeling QoE in interactive tasks like games, web navigation and social media use. This work extends the existing paradigm of QoE measurements that has focused on passive media consumption. The paradigm allows us to test several related questions. For example, it will tell if increased reliability during travel could actually be achieved by multi-homing with mobile networks or if the asset sharing (towers, BS locations etc.) between operators' limits the potential improvement in reliability.

COMPUTED: Computational User Interface Design

This project aims to establish the foundations for solving UI design problems by combinatorial optimization methods that deploy mathematical models of user behavior as objective functions. Given objectives and constraints, a UI is automatically optimized. Previous work in UI optimization shows significant improvements to usability, but the scope has been restricted to virtual keyboards and widget layouts. COMPUTED researches methods that could vastly expand the scope and permit solutions to any well-defined UI design problem. First, objective functions are currently limited to models of sensorimotor performance. COMPUTED develops algorithmic support for acquiring more comprehensive models that cover the main human factors. Second, current work has formally defined only one UI optimization problem, the letter assignment problem. To combat a more relevant set of design problems with appropriate optimization methods, COMPUTED formally analyzes recurring design problems. Third, previous work has followed the "fire- and-forget" approach where the problem is completely predefined for an optimizer. COMPUTED develops a novel interactive UI optimization paradigm that promotes fast convergence to good results even in the face of uncertainties and incomplete preknowledge. The novel capabilities are demonstrated in four hard cases: 1) universal keyboard layout, 2) web applications, 3) hand gesture input, and 4) interactive dashboards in cars.

Optimizing Gestural Interaction

This project investigates an emerging input method enabled by progress in hand tracking: input by free motion of fingers. The method is expressive, potentially fast, and usable across many settings as it does not insist on physical contact or visual feedback. Our goal is to inform the design of high-performance input methods by providing detailed analysis of the performance and anatomical characteristics of finger motion. We conducted an experiment using a commercially available sensor to report on the speed, accuracy, individuation, movement ranges, and individual differences of each finger. Findings show differences of up

to 50% in movement times and provide indices quantifying the individuation of single fingers. We apply our findings to text entry by computational optimization of multi-finger gestures in mid-air. To this end, we define a novel objective function that considers performance, anatomical factors, and learnability.

CORE GROUP

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Dr. Daryl Weir, Postdoc

Dr. Byungjoo Lee, Postdoc (started early 2015)

Anna Feit, PhD student

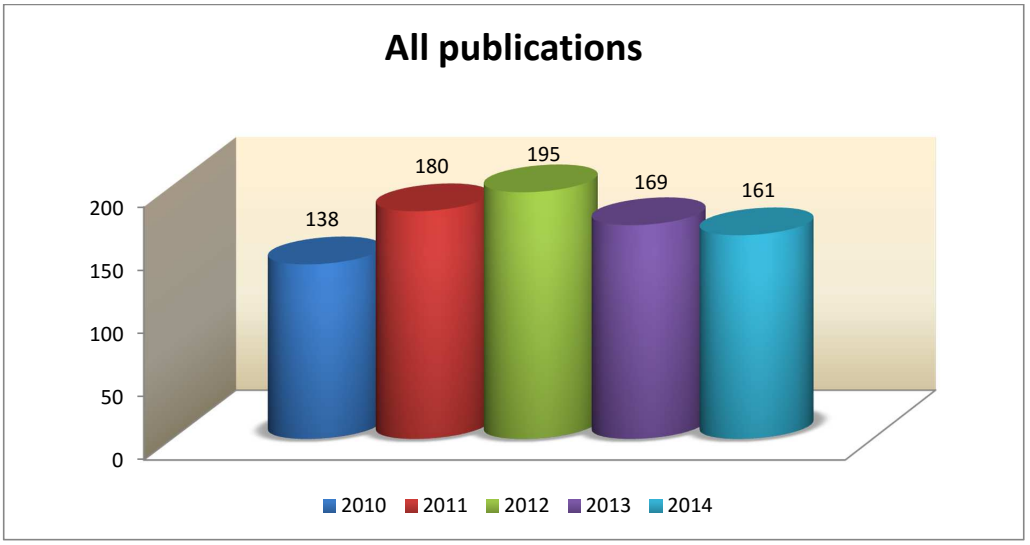
Perttu Lähteenlahti, Research assistant

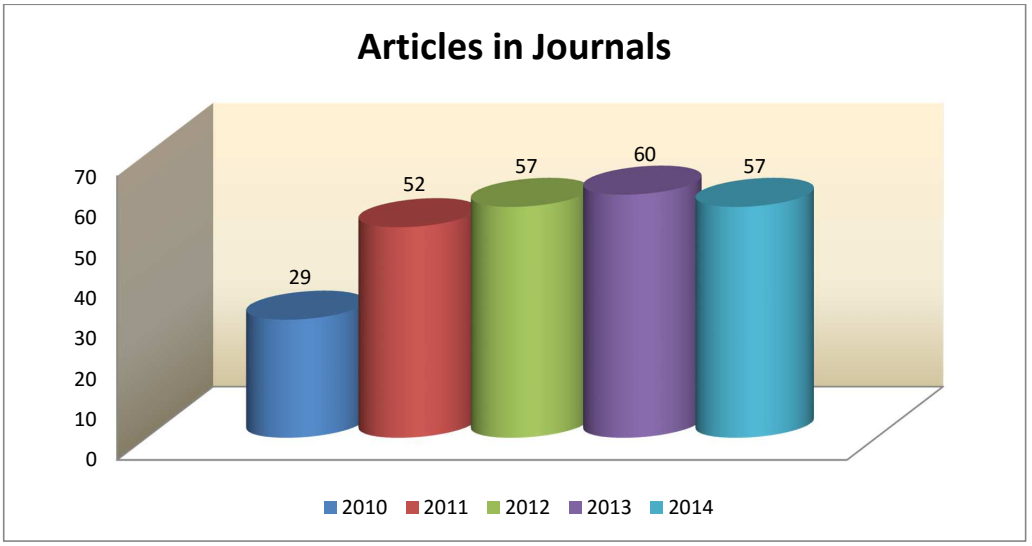
Chen Wang, Master's thesis student (started early 2015)

Gabriela Villalobos, Master's thesis student (started early 2015)

APPENDICES

PUBLICATIONS





ABSTRACTS OF DOCTORAL THESES 2014

Bou Saleh, Abdallah: Inband Relaying in Long Term Evolution-Advanced Networks
Supervisor: Prof. Jyri Hämäläinen

The set of stringent requirements for 4G radio access networks has triggered the embodiment of new small low-power nodes, e.g. relay, Femto and Pico access nodes, as part of the network infrastructure. Various types of relay nodes are currently supported in IEEE 802.16m and 3GPP LTE-Advanced, e.g. inband Layer 2 or Layer 3 nodes and outband nodes, considering different functional capabilities and backhauling characteristics. In general, relay nodes are characterized by compact physical characteristics, low power consumption, a wireless backhaul link to the core network, and relaxed installation guidelines with respect to radiation and planning regulation. In specific, inband relay nodes, the matter of this study, are Layer 3 access nodes with time-multiplexed transmission and reception on their wireless backhaul and access links, which operate on the same frequency band. These characteristics impose serious challenges on one hand, but allow for significant improvements on the other hand.

In this context, the deployment flexibility of relay nodes simplifies the network planning procedure and reduces deployment costs. On the other hand, low power transmission and limited antenna capabilities result in small relay cell coverage areas which will lead to load imbalances. Besides, multiplexing backhaul and access communications on different subframes implies the need for suitable two-hop resource allocation and scheduling. Further challenges are attributed to increased interference levels compared to macrocell deployments, as well as the introduction of a new interference type known as relay-to-relay interference resulting from the misalignment of access and backhaul link dedicated subframes at different relay nodes.

The research towards this thesis has addressed these challenges within 3GPP LTE-Advanced context. A feasibility study of different relaying modes is provided and the performance of relay deployments is evaluated in different propagation environments. Thereafter, simple network planning techniques are proposed to alleviate the limitations of the inband backhaul link. Further, novel techniques are investigated to address resource allocation and scheduling, load balancing and interference coordination. The performance of proposed techniques along with the energy efficiency of relay nodes is evaluated. Results show in general significant gains and validate relaying as an efficient enhancement technology.

Ginzboorg, Philip: Security mechanisms in partially isolated networks
Supervisor: Prof. Jörg Ott

A challenged network is a network subject to difficult operational constraints, like disrupted links and high delays. An example is a mobile ad hoc network where the nodes communicate without infrastructure support. Specifics of such networks are the consequence of intermittent access to (or complete lack of) infrastructure and partial isolation of the network nodes from each other. Partial isolation of the nodes aggravates resource scarcity. In this work we investigate (1) security and privacy, as well as (2) resource management, in these networks. Our thesis is that in partially isolated networks security and privacy, on

the one hand, and resource management, on the other, are closely related and tend to influence each other.

This dissertation includes nine publications. Their summaries are grouped in two chapters. The first, Chapter 2, is about security and privacy issues and also the question of congested buffer management, which we approach via adversarial scenario. In the second, Chapter 3, we consider better utilization of the scarce contact time between the network nodes via message fragmentation when there are intermittent transmission opportunities.

Part of the work comprising this dissertation had industrial impact: I have contributed to the Generic Authentication Architecture standard of 3GPP, described in publication II; and the "Equal Subdomains" technique found in publication IV was included of the Nokia Awarenet platform.

Hiltunen, Kimmo: The Performance of Dense and Heterogeneous LTE Network Deployments within an Urban Environment
Supervisor: Prof. Riku Jäntti

Traffic in the mobile broadband networks is expected to grow very rapidly in the coming years. This traffic growth is caused both by the evolution of mobile terminals and by the increased use of more traffic-heavy services, such as video. In order to be able to meet the increased capacity needs, the existing mobile networks have to be densified, either by deploying new macro sites, or by deploying new low-power sites within traffic hotspots. This doctoral dissertation provides an overview of a few different network densification alternatives and compares their performance and energy-efficiency with the help of advanced radio network simulations. In addition, the impact of different network design choices is evaluated.

The results demonstrate that the heterogeneous network deployments are realistic alternatives to the traditional way of densifying mobile networks by deploying new macro sites. However, the price to pay is that a considerably larger number of new sites will be required to obtain the same network performance. Heterogeneous network deployments can be made more efficient by increasing the output power of the low-power eNodeBs or by carefully planning the locations of the low-power sites so that the obtained level of the traffic offloading can be maximized. The traffic offloading can be increased also with the help of biased cell selection, but in that case the quality of the downlink control signaling can become the limiting factor unless some form of enhanced inter-cell interference coordination mechanisms are applied at the same time.

The obtained results indicate that the densified macro deployment is in many cases the most energy-efficient network densification alternative. However, if some form of fast cell DTX is applied to idle cells, heterogeneous network deployments become much more competitive since the cost of fixed power consumption can be reduced. The energy-efficiency of densified network deployments can be enhanced also by switching off underutilized capacity cells, or by switching idle capacity cells to sleep mode. Finally, design choices aiming to reduce the required number of low-power cells are shown to be beneficial also from the network energy-efficiency point of view.

Levä, Tapio: Feasibility analysis of new Internet protocols: Methods and case studies
Supervisor: Prof. Heikki Hämmäinen

The Internet standardization community actively develops new Internet protocols as a response to challenges with the existing protocols and the requirements of new application areas. However, many of these protocols fail to achieve their expectations due to limited deployment. A significant reason for the lack of deployment seems to be that the stakeholders' incentives and the dynamics of protocol deployment are not sufficiently understood and taken into account during the protocol development. Consequently, new protocols end up being techno-economically infeasible and significant development effort is wasted.

This dissertation aims for improving the techno-economic feasibility of new Internet protocols by increasing the understanding of the dynamics of protocol deployment and the factors affecting the feasibility of Internet protocols. Additionally, the dissertation develops methods for analyzing the deployment and feasibility of Internet protocols. The research builds on three in-depth case studies that apply multiple research methods to analyze the feasibility of multipath TCP, host identity protocol and constrained application protocol. Then, the results of these case studies are combined with the existing literature on innovation diffusion and network economics to construct frameworks for both measuring the deployment and analyzing the feasibility of Internet protocols.

The results show that, due to the protocols' nature as software components embedded in software and hardware products, the technology-push from hardware and software providers affects significantly protocol deployment. The end users may also be unaware that they have acquired, and even started, using protocols. These factors combined result in large gaps between the number of end users possessing a protocol and the number of those using it. The constructed feasibility analysis framework is another key result of the dissertation, as it provides a systematic process description and research method toolbox for identifying the deployment challenges and proposing solutions to them already during the protocol development. Finally, the protocol case studies identify new factors affecting the feasibility of Internet protocols.

The results highlight the importance of analyzing the feasibility of new Internet protocols systematically from the beginning of protocol development, spanning throughout the protocol deployment and covering all the relevant stakeholders. Measuring protocol deployment can support the feasibility analysis by identifying the deployment bottlenecks and improving the understanding of the dynamics of protocol deployment. Systematic, techno-economic feasibility analysis can help protocol developers to improve the feasibility of their protocols and the deploying stakeholders to make more informed deployment decisions.

Mahmood, Aamir: Enabling Time-Synchronized and Interference-Aware Initialization of Wireless Sensor Networks
Supervisor: Prof. Riku Jäntti

Wireless sensor networks (WSNs) provide ad hoc wireless infrastructure to spatially distributed sensors to interact with physical or environmental phenomena. WSNs can offer a multitude of applications given that the sensors are able to collaborate and self-organize. These requirements are essential to accurately capture and reliably fuse the observations towards the application logic. This thesis studies time

synchronization and interference management schemes to enable collaboration and self-organization in low-power WSNs.

Network-wide time synchronization is required both for the concurrent actuation of sensors and reliable data aggregation. Time synchronization is achieved by a clock synchronization algorithm which estimates the clock offset and clock skew at a sensor with respect to a reference time. The reference time is diffused in the network by a messaging protocol. This thesis studies clock offset and skew estimation methods for broadcast-based exchange of the reference time. The offset estimation is based on a study to eliminate the delay factors in the communication path. For skew estimation based on linear-regression, the correlation between time synchronization period and regression size is studied. In addition, a maximum-likelihood skew estimator, which minimizes the estimation error variance, is validated.

From an application's perspective, the time synchronization service should provide the desired synchronization accuracy in a transparent and energy-efficient manner. This thesis demonstrates this ability by extending the proposed time synchronization methods for a) tight synchronization among vibration samples in a structural health monitoring application, b) communication scheduling in time and frequency.

WSNs deployed in shared unlicensed bands need to analyze and mitigate interference. The low-power transmissions of sensor nodes are otherwise prone to corruption from high-power transmissions of coexisting wireless networks. Therein, this thesis proposes coexistence models for energy-detection based link-quality estimation. The coexistence models are utilized to formulate low-complexity coexistence enhancement algorithms named channel ranking. A ranking algorithm creates an ordered list of the candidate channels using a channel quality metric (CQM). The algorithms differ with respect to their design of CQM, the main design factor being the availability of network connectivity information which is usually unknown upon network initialization.

Pitaval, Renaud-Alexandre: Coding on Flag Manifolds for Limited Feedback MIMO Systems
Supervisor: Prof. Olav Tirkkonen

The efficiency of the physical layer in modern communication systems using multi-input multi-output (MIMO) techniques is largely based on the availability of channel state information (CSI) at the transmitter. In many practical systems, CSI needs to be quantized at the receiver side before transmission through a limited rate feedback channel. This is typically done using a codebook-based precoding transmission, where the receiver transmits the index of a codeword from a pre-designed codebook shared with the transmitter. To construct such codes one has to discretize complex flag manifolds. For single-user MIMO with a maximum likelihood receiver, the spaces of interest are Grassmann manifolds. With a linear receiver and network MIMO, the codebook design is related to discretization of Stiefel manifolds and more general flag manifolds.

In this thesis, coding in flag manifolds is studied. In a first part, flag manifolds are defined as metric spaces corresponding to subsurfaces of hyperspheres. The choice of distance defines the geometry of the space and impacts clustering and averaging (centroid computation) in vector quantization, as well as coding theoretical packing bounds and optimum constructions.

For two transmitter antenna systems, the problem reduces to designing spherical codes. A simple isomorphism enables to analytically derive closed-form codebooks with inherent low-implementation

complexity. For more antennas, the concept of orbits of symmetry groups is investigated. Optimum codebooks, having desirable implementation properties as described in industry standardization, can be obtained using orbits of specific groups.

For large antenna systems and base station cooperation, a product codebook strategy is also considered. Such a design requires to jointly discretize the Grassmann and Stiefel manifolds. A vector quantization algorithm for joint Grassmann-Stiefel quantization is proposed. Finally, the pertinence of flag codebook design is illustrated for a MIMO system with linear receiver.

Suomi, Henna: Techno-economic feasibility analysis of multipath protocols in the Internet
Supervisor: Prof. Heikki Hämmäinen

During the past few decades, multipath protocols have been developed to improve load balancing in the Internet. These protocols can send the traffic of individual end users through several paths simultaneously and switch the traffic from one path to another. Despite many technical proposals, multipath protocols are not widely deployed and their economic feasibility remains unstudied.

This research fills the gap by analyzing the economic feasibility of multipath protocols from the perspective of different stakeholders. The research essentially considers the use case of accessing Internet services with mobile devices. The objective of the research is to identify and elaborate the factors affecting economic feasibility of multipath protocols, and also their effects on the Internet connectivity market. Furthermore, this research aims to develop the methods for studying not only the feasibility of multipath but also other Internet protocols. Several methods are employed to attain these objectives. Economic theories of network effects and switching costs are taken as the basis for studying the feasibility. System dynamics and variants of techno-economic modeling are used to model the diffusion process and to elaborate the costs and benefits of multipath protocols. Data collection is based on literature, expert interviews and network performance measurements.

The results indicate that the protocols enabling host-controlled switch of access operators seem initially more compelling than the protocols that allow accessing several operators simultaneously. Especially, three factors are seen to affect the feasibility of multipath protocols positively: 1) growing number of multihoming-capable (e.g., multi-SIM) devices, 2) higher performance requirements of emerging applications, and 3) increasing capacity of batteries. In case of wide-scale deployment, the market impacts of client multihoming and multipath protocols are expected to be significant since they will reallocate the cost and revenue flows of operators and increase competition in the mobile access.

The modeling methods of this research create a novel and practical approach to the research of protocol feasibility. As opposed to traditional economics modeling which neglects the details of a technical structure (black box), techno-economic modeling considers the technical architecture as a white box allowing for the identification of the deployment challenges and opportunities of a protocol. In addition, the research observes that comparing the costs of a protocol against the non-monetary benefits, instead of a purely monetary comparison, is often more applicable approach to the techno-economic analysis of protocols.

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MASTER OF SCIENCE THESES 2014

Author: Topic	**Supervisor**
Alwadi, Ali: Collision Monitoring and Alarm in Ice-Hockey	Riku Jäntti
Appelberg, Jon: Performance Testing of a Network Management System in Challenged Networks	Raimo Kantola
Atsmegiorgis, Asrat Teshome: Study of Error Sources in Mobile Network Time Synchronization	Jörg Ott
Bai, Xue: Scenario Analysis on LTE mobile network virtualization	Heikki Hämmäinen
Boyd, Christopher: Classical Error-correcting Codes in Quantum Communications	Olav Tirkkonen
Boye, Magnus: Measuring Websites from a Global Perspective	Jörg Ott
Costa, Samuel: Mobile Offloading in Residential Wireless Access Markets	Heikki Hämmäinen
Enqvist, Jesse: Measuring customer experience in operator's retail store and on web page	Kalevi Kilkki
Eskelinen, Janne: Mobiilipankkisovelluksen järjestelmätoteutuksen viitekehys	Raimo Kantola
Gebrehiwot, Misikir Eyob: Energy-Aware Queueing Models and Controls for Server Farms	Samuli Aalto
Haile Magicho, Rekik: Application of SDN Concept in Mobile Backhaul for Traffic Optimization	Jukka Manner
Hailu, Sofonias: Dynamic Inter-operator Spectrum Sharing Between Co-located Radio Access Networks Using Cooperation Transmission	Olav Tirkkonen
Hasan, Khalid: Use of Coordinated Multipoint Transmission/Reception for Enhanced Backhauling in Nomadic Relay	Jyri Hämäläinen

Hovaidi Ardestani, Mohammad: Congestion Control in Information Centric Networking using Neural Networks	Jörg Ott
Hämäläinen, Harri: Evaluation of the network performance in a high performance computing cloud	Jukka Manner
Iqbal, Umar: LTE, LTE Advanced and Beyond	Jyri Hämäläinen
Jony, Rabiul Islam: Preprocessing Solutions for Telecommunication Specific Big Data Use Cases	Heikki Hämmäinen
Kabir, Hammad: Security Mechanisms for a Cooperative Firewall	Raimo Kantola
Kebede, Selam: Effects of Quality of service on video-chat users	Kalevi Kilkki
Khalid, Abdulfetah: Load Balancing of Elastic Data Traffic in Heterogeneous Wireless Networks	Samuli Aalto
Kimmerlin, Maël: Caching in LTE networks using Software-Defined Networking	Jukka Manner
Koistinen, Tuukka: Implementation and Evaluation of Security on a Gateway for Web-based Real-Time Communication	Jörg Ott
Kulkarni Vasant, Chandana: Experimental Setup for Cellular User Connectivity Prediction in Cognitive Radio Networks	Olav Tirkkonen
Kyöstilä, Tomi: The effectiveness of evasion techniques against intrusion prevention systems	Jukka Manner
Kärkkäinen, Teemu: Instant Messaging and Presence in Challenged Networks	Jörg Ott
Lavonen, Niko: User centered evaluation and design for improving the usability of the quasar observation system for a radio telescope	Kalevi Kilkki
Lehtonen, Jouko: Hajautetun osoitepalvelun suunnittelu haasteelliseen verkkoon	Raimo Kantola
Liu, Zijia: Cooperative Device-to-Device (D2D) communications as an underlay of future mobile networks	Jyri Hämäläinen
Lu, Xiaohua: Energy-aware Performance Analysis of Queueing Systems	Samuli Aalto
Luukko, Jyrki: Organizational Identity and Access Management Maturity and Techniques for Improvements	Heikki Hämmäinen
Lääperi, Lauri: Common Operating Picture of Critical Infrastructure: System Design and Implementation	Jukka Manner
Martin-Perez, Javier: Providing Carrier Grade voice Services with Session Initiation Protocol	Raimo Kantola
Mobarek, Ahmed: Demand modeling for mobile app stores	Kalevi Kilkki
Ocak, Mert: Implementation of an Internet of Things Device Management Interface	Jörg Ott
Pande, Swapnil: Time Division-LTE Rollout Strategies for Wireless Service Providers in India	Heikki Hämmäinen

Pokhrel, Saurabh: Implementation and Analysis of FLD TCP	Jukka Manner
Puig-Guerra, Jose Luis: Analysing Redundancies in the World-Wide-Web	Jörg Ott
Rantamäki, Jaakko: Implementing Fast Feedback Response in Agile Software Development	Raimo Kantola
Ratilainen, Antti: Protocol Performance of Uplink/Downlink Separation in LTE Heterogeneous Networks	Jyri Hämäläinen
Roisko, Ville: Usability evaluation of TETRA mobile radio in Public Protection and Disaster Relief (PPDR) vehicles	Kalevi Kilkki
Saarnia, Kai: IPv6-käyttöönotto palveluntarjoajan konesaliverkossa	Jukka Manner
Sallinen, Soile: Ohjelmistoradion lähettimen epälineaarisuuden karakterisointi	Riku Jäntti
Salo, Heikki: Verkkopalveluiden käytettävyysongelmat ja niiden luokitus	Jyri Hämäläinen
Setälä, Kim: Mobiililaajakaistan käyttökokemus	Jukka Manner
Shao, Qiwen: Comparison of different MIMO-OFDM signal detectors for LTE	Olav Tirkkonen
Singh, Bikramjit: Repeated Games For Inter-operator Spectrum Sharing	Olav Tirkkonen
Sirén, Petteri: The Use of Locator/ID Separation Protocol in Providing Network Services by Internet Service Providers	Raimo Kantola
Studers, Mikelis: Improvements of 2.4 GHz radio based wireless microphone system	Riku Jäntti
Subramanya, Tejas: Performance evaluation of Dynamic Block Error target selection based on traffic types in High Speed Uplink Packet Access	Riku Jäntti
Tabakov, Boyan: Techno-Economic Feasibility of Web Real-Time Communications	Heikki Hämmäinen
Taha, Abdalla: Software-Defined Networking and its Security	Jukka Manner
Thapa, Jitendra Raj: Automatic Neighbor Relation in Self-Organizing Heterogeneous Networks	Jyri Hämäläinen
Tiilikainen, Seppo: Improving the National Cyber-security by Finding Vulnerable Industrial Control Systems from the Internet	Jukka Manner
Wallenius, Jonatan: State-of-the-art and User Requirements of Blood Glucose Measurement: Devices, Software and Services	Jyri Hämäläinen
Veijalainen, Teemu: Beam steering in millimeter wave radio links for small cell mobile backhaul	Jukka Manner
Vesselkov, Alexandr: Forecasting of mobile handset feature diffusion: supply-related aspects	Heikki Hämmäinen
Virtanen, Jukka-Pekka: Measuring Mobile Networks with Smart Phones	Jukka Manner

ACTIVITIES IN 2014

SCIENTIFIC ACTIVITIES

Riku Jäntti:

- **Membership of editorial board of scientific journals;** IEEE Transactions on Vehicular Technology, USA.
- **Opponent** to Jussi Turkka, Tampere University of Technology.
- **External Examiner of Doctoral Thesis**, Umar Abu Ella, University of Vaasa.

Olav Tirkkonen:

- **Opponent** to Maksym Girnyk, KTH (member of committee), Sweden.
- **Opponent** to Alu Özyagci, KTH (member of committee), Sweden.
- **External Examiner of Doctoral Thesis**, Jacobus Vlok, University of Tasmania.
- **External Examiner of Doctoral Thesis,** Sener Dikmese, Tampere University of Technology.

Jyri Hämäläinen:

- **Opponent** to David González, Universitat Politecnica de Catalunya.
- **Opponent** to Marko Höyhtyä, University of Oulu.
- **Opponent** to Frans Laakso, University of Jyväskylä.
- **External Examiner of Doctoral Thesis**, Muhammad Usman Sheikh, Tampere University of Technology.

Heikki Hämmäinen:

- **Membership of editorial board of scientific journals**: Telecommunications Policy, Holland.
- **Opponent** to Daniel Adjin, Aalborg University.
- **External Examiner of Doctoral Thesis**, Du Ho Kang, KTH Royal Institute of Technology.

Patric Östergård:

- **Position of trust** in international organizations; COST-Action IC1104: Random Network Coding and Designs over GF(q), Belgium, Management Committee Member.
- **Editor of scientific journals (responsible editor)**; Journal of Combinatorial Designs, USA.
- **External Examiner of Doctoral Thesis**, Mohammadreza Jooyandeh, Australian National University.

Jörg Ott:

- **Opponent** to Andrea Hess, University of Vienna.

Jukka Manner:

- **Membership of editorial board of scientific journals**; Springer in Wireless Networks, Germany.

Antti Oulasvirta:

- **Position of trust** in international organizations; French Academy of Sciences, Valuer.
- **Editor of scientific journals** (responsible editor; International Journal of Human-Computer Studies, USA.
- **Membership of editorial board of scientific journals**; IEEE Computer, USA.
- **Opponent** to Stanislaw Zabramski, Uppsala University.
- **Opponent** to Claudia Krehl, University of Nottingham.
- **External Examiner of Doctoral Thesis**, Jussi Rantala, University of Tampere.

Taleb Tarik:

- **Advisory Board member**, IEEE Communications Standards Supplement at IEEE Communications Magazine.
- **Associate editor**, IEEE Transactions on Wireless Communications.

Zheng Yan:

- IEEE Communications & Information Security Technical Committee, **Committee Member**, U.S.A.
- National "863 projects" of Chinese Scientific and Technology Ministry, **Project Referee**, China.
- **Editor of scientific journals (responsible editor):**
    - Future Generation Computer Systems (Elsevier), Netherlands.
    - Information Fusion (Elsevier), Netherlands.
    - IEEE Systems Journal, U.S.A.
    - Computers & Security (Elsevier), Netherlands.
    - Security and Communication Networks (Wiley), U.S.A.
    - International Journal of Communication Systems (Wiley), U.S.A.
    - ACM/Springer Mobile Networks and Applications (Springer), Germany.
- **Membership of editorial board of scientific journals:**
    - KSII Transactions on Internet and Information Systems, Korea.
    - Security and Communication Networks (Wiley), U.S.A.
- **External Examiner of Doctoral Thesis**, Liu Meirong, University of Oulu.

DUTIES IN INTERNATIONAL CONFERENCES

Riku Jäntti:

- IEEE GLOBECOM 2014 Green Broadband access: energy efficient wireless and wired network solutions (GBA) Austin USA, 12.12.2014; **Membership of the program or organizing committee.**

Olav Tirkkonen:

- International Conference on Cognitive Radio Oriented Wireless Networks (CrownCom), 2014, Oulu, 2.-4.6. 2014; **Membership of the program or organizing committee**.

- IEEE Global conference on telecommunications, Austin, Texas, USA, 8.-12.4. 2014; **Membership of the program or organizing committee**.
- IEEE Vehicular Technology Conference, Seoul, Korea, 18.-21.5. 2014; **Membership of the program or organizing committee.**

Esa Hyytiä:

- IEEE Infocom, Toronto, Canada, 27.4-2.5.2014IFIP Networking, Trondheim, Norway, 2-4.6.2014; **Membership of the program or organizing committee.**
- IFIP International Conference on Network and Parallel Computing (NPC), Taiwan, 18-20.9.2014; **Membership of the program or organizing committee.**
- ACM/IEEE/IFAC/TRB International Conference on Connected Vehicles & Expo (ICCVE), Wien, Austria, 3-7.11.2014; **Membership of the program or organizing committee.**
- International Conference on Internet of Vehicles, Beijing, China, 1-3.9.2014; **Membership of the program or organizing committee.**

Patric Östergård:

- 4th International Castle Meeting on Coding Theory and Applications, Portugal; **Chairman of the session**.
- 4th International Castle Meeting on Coding Theory and Applications, Portugal; **Membership of the program or organizing committee.**

Samuli Aalto:

- ACM SIGMETRICS 2014, International Conference on Measurement and Modeling of Computer Systems, Austin, TX, USA, 16.-20.6.2014; **Membership of the program or organizing committee.**
- ECQT 2014, 1st European Conference on Queueing Theory, Ghent, Belgium, 20.-22.8.2014; **Membership of the program or organizing committee.**
- ITC 26, 26th International Teletraffic Congress, Karlskrona, Sweden, 9.-11.9.2014; **Membership of the program or organizing committee.**

Jukka Manner:

- IEEE Asia Pacific Conference on Wireless and Mobile 2015; **Membership of the program or organizing committee**.
- IEEE PIMRC 2014; **Membership of the program or organizing committee**.

Taleb Tarik:

- **Keynote**, Int'l Conf. on Wireless Communications (WINCOM), Rabat, Morocco, Dec. 2014.

Zheng Yan:

- **Steering committee** of IEEE International Conference on Computer and Information Technology, Committee Member, U.S.A.

- The Third International Conference on Advances in Vehicular Systems, Technologies and Applications, June 22-26, 2014, Seville, Spain; **Membership of the program or organizing committee.**
- ICSOC (2014) 12th International Conference on Service Oriented Computing (A class), Paris, France, Nov. 3-6, 2014; **Membership of the program or organizing committee**.
- The 3rd International Conference on Smart Systems, Devices and Technologies, July 20 - 24, 2014, Paris, France; **Membership of the program or organizing committee**.
- The 12th IEEE International Conference on Dependable Autonomic and Secure Computing, Aug 24 - 27, 2014 – Dalian, China; **Membership of the program or organizing committee**.
- The 5th International Workshop on Wireless Networks and Multimedia, Dalian, China, Aug. 24-27, 2014; **Membership of the program or organizing committee**.
- The 1th International Conference on Internet of Vehicles, Aug. 27-29, 2014, Beijing, China; **Membership of the program or organizing committee**.
- The 12th IEEE International Conference on Embedded Computing, Aug 24 - 27, 2014 – Dalian, China; **Membership of the program or organizing committee**.
- The 3rd International Conference on Connected Vehicles & Expo (ICCVE 2014), Nov 3-7, 2014, Messe Wien, Vienna, Austria; **Membership of the program or organizing committee.**
- The 4th International Conference on Mobile Services, Resources and Users (Mobility 2014), July 20 - 24, 2014 - Paris, France; **Membership of the program or organizing committee**.
- The 12th IEEE International Conference on Green Computing and Communications, Sep 1 - 3, 2014, Taipei, Taiwan; **Membership of the program or organizing committee.**
- ASE BigDataScience 2014 International Workshop on Context Discovery and Data Mining, 4 - 7 August, 2014, Beijing, China; **Membership of the program or organizing committee.**
- The 14th IEEE International Conference on Computer and Information Technology (CIT2014), Xi'an, China; **Chairmanship**.
- The 6th International Symposium on Cyberspace Safety and Security (CSS2014), Paris, France; **Chairmanship**.
- The IEEE International Symposium on Recent Advances of Computer and Information Technologies (RACIT2014), Xi'an, China; **Chairmanship**.
- The IEEE International Workshop on Data, Text, Web and Social Networking Mining (WTWSM2014), Xi'an, China; **Chairmanship**.
- The 2014 9th International Conference on Broadband and Wireless Computing, Communication and Applications, Guangzhou, China; **Chairmanship**.

Marttinen, Aleksi:

- Military Communications Conference (MILCOM), Baltimore, MD, USA, 6-8.10.2014, USA; **Participation/presentation**.
- IEEE Conference on Communications and Network Security, San Francisco, CA, USA, 29-31.10.2014; **Participation/presentation**.

Mutafungwa, Edward:

- Cooperation with Finnish Institutions: Highlighting Expertise and Partnership Opportunities at IST Africa Conference 2014 held in Mauritius on 06 – 09 May 2014; **Participation/presentation**.

REWARDS

Esa Hyytiä:

- **Best Paper Award**, admitted by ITC 26 (26th International Teletraffic Congress, Karlskrona, Sweden, 9.-11.9.2014).
- **Distinguished Member** of the 2015 IEEE INFOCOM Technical Program Committee, admitted by IEEE Communications Society, USA.

Samuli Aalto:

- **Best Paper Award**, admitted by ITC 26 (26th International Teletraffic Congress, Karlskrona, Sweden, 9.-11.9.2014

Antti Oulasvirta:

- **Honorable Mention** for a full paper, myöntäjä: ACM SIGCHI, USA.

Zheng Yan:

- **IEEE Outstanding Leadership Award** at IEEE CIT 2014, admitted by IEEE CIT2014 Steering Committee, U.S.A.
- **IEEE Outstanding Service Award** for IEEE RACIT 2014 Organization, admitted by IEEE CIT2014 Organization Committee, China.
- **IEEE Outstanding Service Award** for IEEE DTWSM 2014 Organization, admitted by IEEE CIT2014 Organization Committee, China.
- **Outstanding Leadership Award** at IEEE HPCC/ICESS/CSS 2014, admitted by IEEE HPCC/ICESS/CSS2014 Organization Committee, France.
- **Excellent Individual from Abroad** in Shaanxi Province 2014, admitted by Shaanxi Province foreigner affair office, China.
- **The Best Faculty** in Academic Year 2013 - 2014, admitted by Xidian University, China

VISITS ABROAD

Jyri Hämäläinen:

- Addis Ababa Institute of Technology, Ethiopia; **teaching**, 7 days.

Antti Oulasvirta

- Max Planck Institute for Informatics, Germany, 3 months, reason of visit: **Research**.

Kalle Ruttik:

- CoICT, University of Dar es Salam, Tanzania, 2 weeks, reason of visit: **Teaching.**
- AAIT, Addis Ababa Institute of technology, Ethiopia, 2 weeks, reason of visit: **Teaching**.

Zheng Yan:

- Xidian University, China, 3 months, reason of visit: **Teaching and research**.

Zhou, Liang:

- Northwestern University, USA, 1 months, reason of visit: **Research**.

Marttinen, Aleksi:

- Worcester Polytechnic Institute, USA, 6 months, reason of visit: **Research**.
- Worcester Polytechnic Institute, USA, 6 months, reason of visit: **Postgraduate studies**.

Mutafungwa, Edward:

- Addis Ababa Institute of Technology, Addis Ababa University, Etiopia, 10 days, reason of visit: **Teaching**.
- University of Dar es Salaam, Tansania, 10 days, reason of visit: **Teaching and research**.
- The Bordeaux School of Public Health (Institut de Santé Publique, d'Epidémioloie et de Développement – ISPED), Université Bordeaux, Ranska, 3 days, reason of visit: **Research**.

Esa Hyytiä

- Carnegie Mellon University, USA, 1 month, reason of visit: **Research**.

FOREIGN VISITORS

- Brumby, Duncan from University College London, UK.
- Calderbank, Robert from Duke University, USA.
- Garcia-Lozano, Mario from Universitat Politècnica de Catalunya, Spain.
- Hornbaek, Kasper from University of Copenhagen, Denmark.
- Johansson, Mikael from KTH Royal Institute of Technology, Sweden.
- Jonckheere, Matthieu from University of Buenos Aires, Argentina.
- Kamsu-Foguem, Bernard from Ecole Nationale d'ingénieurs de Tarbes, France.
- Lin, Dengsheng from University of Electrical Science and Technology of China, China.
- Lyytinen, Kalle from Case Western Reserve University, USA.
- Mähönen, Petri from RWTH Aachen University, Germany.
- Rinat, Kashaev from Universite de Geneve, Switzerland.
- Stevens, Brett from Carleton University, Canada.
- Tafazolli, Rahim from University of Surrey, UK.
- Tornell, Sergio from Universitat Politècnica de Valéncia, Spain.
- Tsudik, Gene from University of California, USA.
- Uykan, Zekeriya from Dogus University, Turkey.
- Woldegebreal, Dereje Hailemariam from Addis Ababa Institute of Technology, Ethiopia.
  Yonazi, Jim from Institute of Finance Management, Tanzania.

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