



## RESEARCH RESULTS REPORT



# Critical technologies towards 5G

Editor:

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Public

## Preface

This report has been made within VTT's innovation programme *Critical technologies towards 5G* that has operated from the beginning of the year 2013. The programme was set up to develop VTT's competences and offering in the important area of the fifth generation (5G) mobile networks including also critical infrastructure communications. The report gives an overview to many example research results obtained within the programme. The research work has been made in tens of projects from jointly funded EU, Celtic-Plus, Tekes – the Finnish Funding Agency for Innovations, etc. projects to VTT's own projects and commercial projects (e.g., ESA projects). Unfortunately, acknowledging all important persons providing funding, support, and collaboration is not possible in this wide area of work. Hence I warmly thank everyone who has collaborated with us for these results.

Then it is my pleasure to give warmest thanks to all VTT's project managers and key persons who have found time to contribute to this report. And I know there are many more VTT's researchers and managers behind these results and obtaining funding for the work. I appreciate your efforts a lot. Especially I thank Sami Kazi for suggesting making this report and giving many practical guidelines during the process, Pertti Raatikainen for fruitful discussions, and Aarne Mämmelä for sharing his broad increasing knowledge on 5G.

Especially, I wish you will find many interesting research topics, results and ideas from this report. In case you have any comments, questions or collaboration ideas with us please contact us. We will be more than happy for further discussions.

Oulu 24.9.2015

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## 1 Introduction

Research and development of the fifth generation (5G) mobile networks has started strongly. European Commission sees that “5G will be the very backbone of the new digital economy” [1]. This highlights that 5G is not just expected to provide fast Internet for everyone but also to enable new fast business opportunities and ecosystems; introduction of networked and [smart cities](#) [2], vehicles and machines; and reliable and secure communications for critical infrastructures and services. More information for 5G use cases and scenarios can be found in [NGMN 5G white paper](#) [3].

Many of the new foreseen 5G technologies are included in Fig. 1 [4] that is based on [1][5][6]. These new technologies are seen to provide seamless high quality user experience. Device centric connectivity is beneficial for being able to use the best networks available in a heterogeneous environment. The role of video streaming is strong as mobile video traffic was 55 % of all mobile traffic already in year 2014 [7]. For exponentially increasing capacity need, new spectrum will be used with smaller cells and advanced multi-antenna systems. Energy efficiency and power saving requires special emphasis in 5G to compensate both the dramatic data volume increase and introduction of battery operated low power sensors and machines. A goal is to cut energy consumption of the whole network to half while providing 1000-fold larger traffic volume after the next decade [3]. Reliable communications is needed e.g. for automated driving, networked robots, remote health monitoring and in coping with natural disasters [3]. Security will also become increasingly important as more and more critical services are provided by wireless networks.

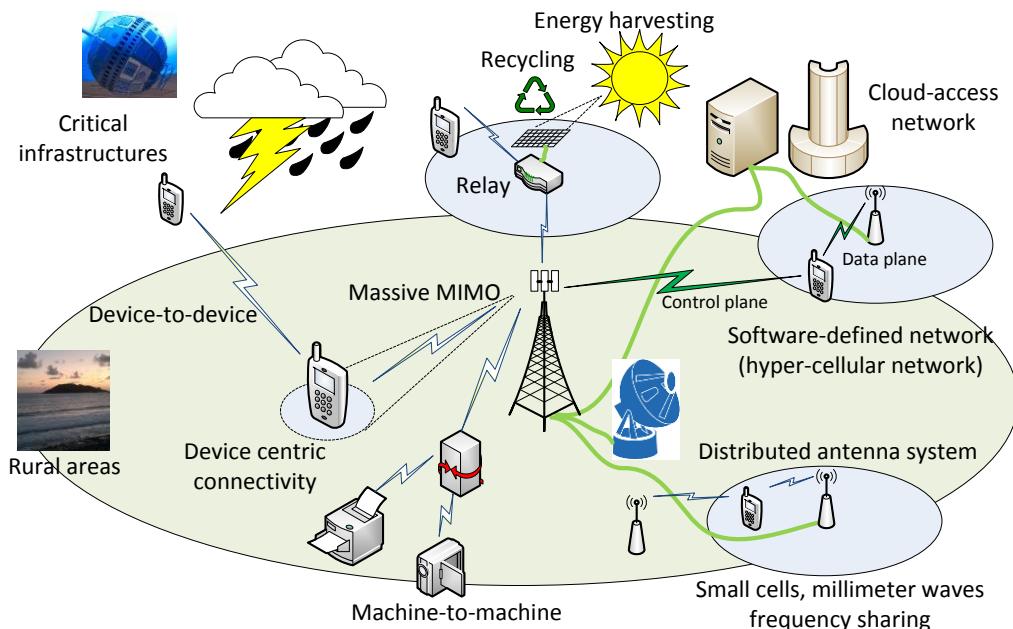


Figure 1. Technologies and use cases for 5G.

For this report, we have selected research result examples for many important 5G areas. First, Section 2 presents solutions for maximising user experience in wireless service delivery covering also device centric approaches, video streaming, and a critical health care application. Then, we study enablers for improving system capacity in Section 3. The approaches include spectrum sharing for both terrestrial and satellite systems, algorithms for reconfigurable antenna based dynamic spectrum access, massive multiantenna system enabler, and millimetre wave radio technologies for 5G. Hence, we cover both using existing frequencies more efficiently and introducing millimetre waves as new wide frequency area for mobile broadband. Energy efficiency is topic of Section 4 starting with consequences from thermal noise death of Moore’s law, and continuing with many solutions for improving energy efficiency of heterogeneous cellular networks. More in detail, we study the potential of using learning techniques to employ complex heterogeneous networks more efficiently. In addition, we present energy efficient radio resource management framework for distributed antenna systems. Then, we concentrate on energy efficient basestation transmission. Section 5 focuses on reliability of critical infrastructures. First, a tool for analysing interdependencies between electricity distribution and telecommunications networks in various fault scenarios is presented. This work has been motivated by

having severe outages due to storms in Finland in recent years. In addition, we discuss physical layer security in two separate subsections. This is a new potential approach for defending against threats and attacks in wireless networks. Then, many network technologies and environments used and developed at VTT are discussed in Section 6. This section starts with presenting control framework evolution view and shows then practical developments done or planned for testing new 5G technologies in real environments. For instance, details are given about the [5G test network](#) project in Section 6.2, and a cost efficient mesh network approach applicable e.g. in rural areas is discussed in Section 6.4. Finally in Section 7 we list many example publications to which VTT has contributed.

#### References for introduction

- [1] [Why the EU is betting big on 5G - Research\\*eu Focus Magazine](#), no. 15, European Union, 2015.
- [2] [Smart City — Research Highlights](#), VTT Research Highlights 12, Editors: Miimu Airaksinen and Matti Kokkala, Feb. 2015.
- [3] [5G White Paper](#), NGMN Alliance, 17 Feb. 2015.
- [4] Aarne Mämmelä, [Energy efficiency in 5G mobile networks](#), keynote talk, [Networking 2015](#), May 2015, Toulouse, France.
- [5] J. G. Andrews et al. "What will 5G be?" IEEE Journal on Selected Areas in Communications, vol. 32, pp. 1065 – 1082, June 2014.
- [6] B. Boccardi et al., "Five disruptive technology directions for 5G," IEEE Communications Magazine, pp. 74–80, Feb. 2014.
- [7] [Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014–2019 White Paper](#), Feb. 3, 2015.

## **2 Providing high quality user experience**

- 2.1 Autonomous management of video streaming services in heterogeneous multi-access networks for optimal user experience**
- 2.2 Evaluation of wireless access selection mechanisms for enhanced network load balancing and user experience**
- 2.3 Avoiding mobile video streaming interruptions via network delay prediction**
- 2.4 Solutions for improved robustness of wireless multimedia communications in critical healthcare scenarios**



## 2.1 Autonomous management of video streaming services in heterogeneous multi-access networks for optimal user experience



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Future internet will be highly heterogeneous in supporting a multitude of access technologies and networks with overlapping coverages. Optimization of network operations such as resource, mobility or Quality of Service (QoS) management in order to ensure smooth network operation and high user satisfaction (Quality of Experience, QoE) will be very challenging in such a multi-access and multi-operator network environment. This will be especially true for QoS-sensitive and network resource consuming video services that already now dominate the data traffic in wireless networks. Automation of network management operations with tolerance to uncertainty will be the key to building sustainable and manageable networks of the future. Cognitive network management can provide the means for this.

### Cognitive network management solution for video streaming optimization

Cognitive networks comprise features such as self-awareness, self-configuration, self-healing, self-optimization, and self-protection, which all can be achieved through knowledge representation and cognitive (learning) loops. VTT has applied the concept of cognitive network management in the optimization of video streaming performance in heterogeneous multi-access networks. The proposed solution addresses the topical problem of finding means to manage the constantly increasing video traffic loads over wireless and providing acceptable QoE to the end users. Thanks to the in-built cognition, VTT's solution operates autonomously, releasing the operator personnel and end users from performing dynamic management tasks and making complex decisions.

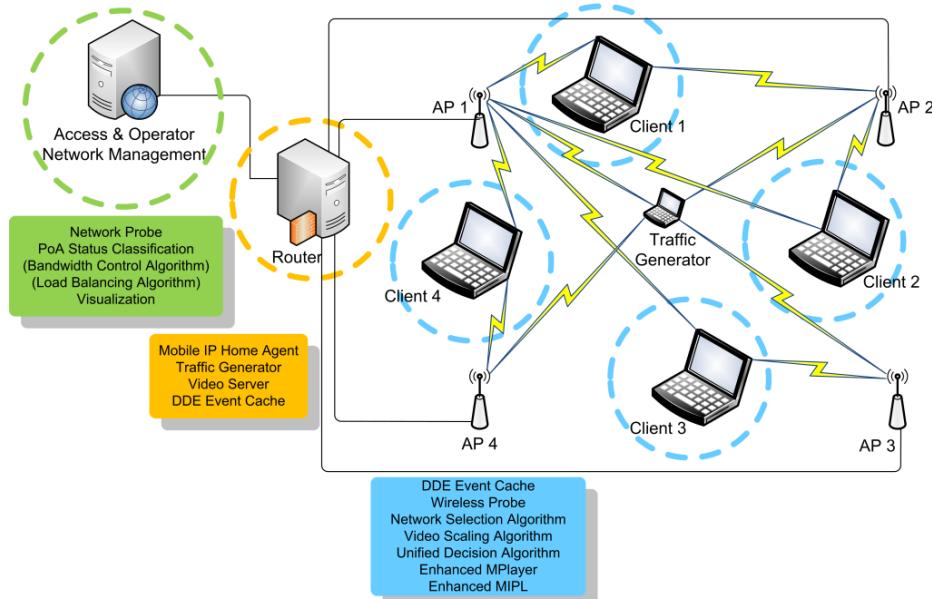
The proposed solution builds upon a cognitive network management architecture, which is based on VTT's Distributed Decision Engine (DDE) concept. For the video streaming optimization, the architecture supports intelligent and autonomous decisions regarding user terminal mobility and video bitrate adaptation as well as their enforcement in heterogeneous multi-access networks. In the architecture, DDE facilitates event-based knowledge building and dissemination between and within (i.e. cross-layer) network nodes. The decision-making is based on novel algorithms implemented using cognitive techniques, including self-organizing map (SOM), fuzzy logic, and reinforcement learning (esp. Q-learning). The algorithms are arranged hierarchically in order to support local optimization and scalability.

The management system supports flexible and gradual deployment of the decision algorithms depending on the scenario. Six different algorithms have been defined for the video streaming optimization and they are intended either for the mobile device (i.e. video client) or the network. The network-side algorithms may be deployed in hierarchy in order to support multiple levels of management and scalability. Moreover, they can take decisions on mobility and resource allocation across multiple mobile devices whereas the client-side algorithms attempt to maximize each mobile device's own condition (i.e. QoE). Coordination and control over the multiple algorithms and decisions are implemented into the Unified Decision Algorithm, which selects and triggers the most appropriate optimization action in a given situation.

### Experimental systems and validation

VTT has developed prototypes of the cognitive network management system and coordinated decision algorithms. The experimental systems realize intelligent and dynamic bitrate adaptation and access network selection for an adaptive HTTP video streaming service in a multi-access network environment. The validation has been done in both testbed and simulator environments. Fig. 1 illustrates the testbed configuration. The network-side algorithms given in parenthesis were not included in the testbed but evaluated in a network simulator. More details on the simulation study are given in Section [2.2](#). Overall, the evaluation results attest

the feasibility of the proposed solution and show the benefits of the cognitive decision techniques over non-learning or non-adaptive approaches.



**Fig. 1. Cognitive network management testbed for mobile video streaming optimization.**

## Discussion

Cognitive network management can provide a solution for managing the complex networks of the future. VTT's proposed solution for cognitive network management of video streaming in heterogeneous multi-access networks addresses the topical problem of finding means to manage the constantly increasing video traffic loads over wireless and providing acceptable QoE to the end users. The solution can be used for enhancing video streaming performance in multi-access networks, and it may also be adapted to support other types of applications as well as multiple simultaneous applications. Improvements to the management system's stability and tolerance to uncertainty are provided in two aspects: learning algorithms can reduce the ping-pong effect, and the use of multiple information sources helps the algorithms to cope with corrupted or incomplete information. Yet, there is a trade-off between video streaming performance and generated signalling overhead. Thus, scalability is one topic to be addressed in future work. Overall, the current results provide a good basis for further development of the cognitive network management solution as well as applying it in other use cases in future projects. Cognitive network management also plays an important role in 5G network design and development.

## Acknowledgments

The work was partly supported by the Finnish Funding Agency for Technology and Innovation (Tekes) and VTT in the frameworks of the EUREKA/Celtic COgnitive network ManageMent under UNCERTainty (COMMUNE) and Energy-Aware Learning in Cognitive Radios and Networks (AWARENESS) projects.

## Related publications

T. Ojanperä, "Cross-layer Optimized Video Streaming in Heterogeneous Wireless Networks", *Ph.D. thesis*, University of Oulu, Finland, June, 2013. URL: <http://urn.fi/urn:isbn:9789526201511>.

M. Luoto, T. Rautio, T. Ojanperä & J. Mäkelä, "Distributed Decision Engine - An Information Management Architecture for Autonomous Wireless Networking", Mini-Conference of the IFIP/IEEE Integrated Network Management Symposium (IM 2015), Ottawa, Canada, May 2015.

## Demo video

The COMMUNE project's demo video is available in YouTube: <http://youtu.be/FTb0tYQKeVI>.

## 2.2 Evaluation of wireless access selection mechanisms for enhanced network load balancing and user experience



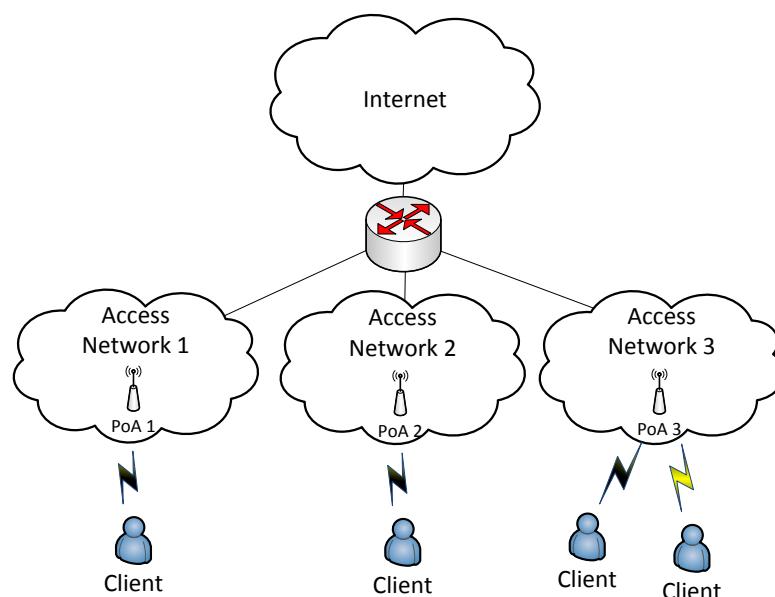
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This work expands the work done in the previous Section 2.1 by providing scalability analysis of different wireless access selection mechanisms that use the concepts of learning and cognition to optimize user experience and enhance network load balancing. Generally the actions of all users influence the whole network and there needs to be a suitable mechanism to optimize the experience of all users.

### Wireless access selection mechanisms

In the work under this topic, the purpose has been to enhance wireless network load balancing by developing different wireless access selection schemes at the client and network side. The client side access selection is a distributed algorithm, in which the clients themselves make the decision when to switch to another Point of Access (PoA). Network side access selection relies on a centralized architecture, where a single decision entity is responsible for all handover decisions within a region. A combination of the client and network side solutions is a hybrid approach in which both central entity and the clients themselves are simultaneously able to make handover decisions.

We have developed a Q-learning based client side access selection algorithm and a load balancing (LB) algorithm for the network side access selection. The Q-learning algorithm allows the mobile nodes to improve the decisions they make by learning from experience. The decisions are based on the current state of the network and expected rewards per possible actions. The LB algorithm is a centralized algorithm that responds to congestion occurring in PoAs by moving a single client, several clients or part of the client's traffic from an overloaded PoA to other overlapping PoAs that may belong to same or different radio access technologies. An overview of the network load balancing scenario can be seen in Fig. 1, in which users have the possibility to connect to several PoAs. The main goal of both algorithms is to provide good Quality of Experience (QoE) for all clients by determining the PoA to connect within all available access networks without triggering too many handovers.



**Fig. 1. Network load balancing scenario overview.**

## Simulation and validation

The network access selection mechanism at the client side was first studied. A greedy access selection method was compared to the Q-learning based access selection method in a situation when the access network gets congested. The former method switched to the best available network whenever needed, while the latter tried to learn an optimal policy for user initiated handovers. Performance evaluation showed that the Q-learning method was able to outperform the deterministic handover decision mechanism. The number of handovers was reduced while a suitable QoE was still provided to the clients. The evaluation included a file download scenario in a WLAN environment.

Performance evaluation between client side Q-learning algorithm, network side LB algorithm, conventional method of not executing handovers and a greedy access selection algorithm was also done by simulation in a scenario where both file download and progressive video streaming applications were present. The results showed that both Q-learning and LB algorithms were able to improve the users' QoE and distribute the resources better even when multiple applications were simultaneously present in the network. The LB algorithm was able to do resource optimization with a minimal number of total handovers since it used a centralized approach having knowledge about all the PoAs and clients. The number of total handovers was also kept to a minimum with the Q-learning algorithm as it learned an optimal policy for user initiated handovers thus mitigating unneeded actions.

The Q-learning and LB algorithms were also evaluated in a scenario where different user subscription classes were present. Both approaches were able to improve the QoE of the users in a wireless network compared to the conventional method of not executing any handovers. With the LB algorithm, it is more efficient to incorporate user class based policies into the wireless access selection process. For example, if the capacity of the network is clearly not enough to serve all user classes, it is possible to define a policy in which the higher subscription class users are preferred over lower subscription class users.

## Discussion

The wireless access selection is a complex problem and intelligent solutions instead of deterministic ones are needed to manage it. Generally both introduced client side and network side wireless access selection mechanisms require a certain amount of monitoring information from the network in order to make appropriate decisions. If too much overhead is produced in the network, congestion may ultimately occur. In general, a hybrid method including coordination between client and network based access selection mechanisms seems to be a promising solution. Network based load balancing mechanism should be functioning in larger time scales and thus solving the more permanent and serious resource problems, whereas the distributed algorithms are able to react fast but missing the larger view and user class differentiation.

## Acknowledgements

This research has been performed within the Energy-Aware Learning in Cognitive Radios and Networks (AWARENESS) project. The work was also supported by the Finnish Funding Agency for Technology and Innovation (Tekes) in the framework of the EUREKA/Celtic COMMUNE.

## Related publications

O. Mämmelä, P. Mannersalo, "Cognitive Wireless Access Selection at Client Side: Performance Study of a Q-learning Approach," Proceedings of the IEEE/IFIP Network Operations and Management Symposium (NOMS), Krakow, Poland, 5-9 May 2014 (2014).

O. Mämmelä, P. Mannersalo, "User-centric vs Network-centric Load Balancing: how to provide good QoE for gold users," International Journal of Network Management, Special Issue: Advances in Management of Multimedia Services, Volume 25, Issue 4, pages 242–259, July/August 2015.

## 2.3 Avoiding mobile video streaming interruptions via network delay prediction

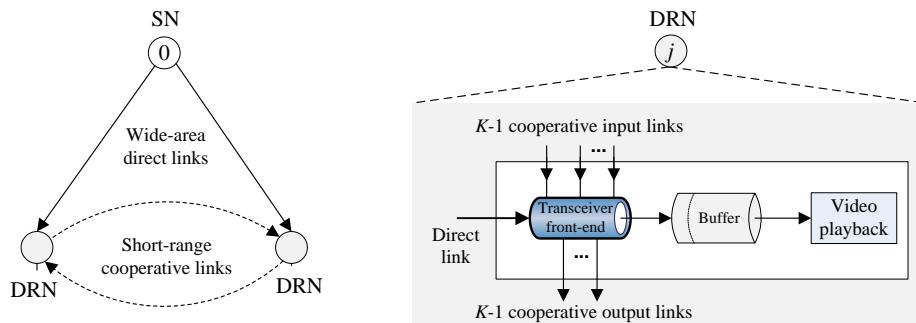


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### Introduction

Wireless video streaming is gaining more and more popularity among mobile users. It is important, for both the content providers and wireless network designers of the future, to understand how to ensure a satisfactory quality of user experience (QoE). There are several video artifacts that affect the QoE. One of the most common problems is the video interruption or screen freeze caused by an empty playback buffer. Consequently, the probability that no interruptions take place during the playback becomes an important metric. The video interruptions can be avoided by using a sufficient playback buffer preloading before the playback starts or adjusting the video resolution to be compatible with the random delay characteristics of the wireless network. This would require that there is a simple analytical tool to predict on which conditions the video interruption probability becomes negligible.

The novelty of our work is three-fold. Firstly, our analytical result provides new inference on how the video length and known statistical delay parameters influence the interruption probability in a simple closed form. Secondly, a useful threshold is presented to select between the proposed method and an asymptotic method whose relative accuracy changes with the video length and statistical properties of the buffer load size. The analysis leads to a novel composite parameter estimation method which is demonstrated using appropriate simulations in a selected streaming scenario. Thirdly, we consider cooperative video transmission approaches to avoid video interruptions in a wireless real-time video streaming system.



**Fig. 1. General system model for proactive prevention of video interruptions in a cooperative network.**

### Framework for proactively preventing video interruptions

In this section, the general system model assumptions are shortly described. We consider a streaming system depicted in Fig. 1 where a mobile user is receiving a video file from a source node via a wireless link with a random packet delay jitter. The source node is assumed to be a base station of a cellular system or another user terminal in case of a peer-to-peer streaming network. The video streaming between the nodes is accomplished by dividing the video file into packets with a suitable length for transmission. At the user terminal, the receiver provides demodulated packets to a playback buffer which is used to partly overcome the network dynamics. The playback buffer stores a selected number of video packets before the video playback starts. Due to wireless network dynamics, the video packets arrive with random delays to the playback buffer. Furthermore, the variable bite rate video encoding method of the MPEG-4 standard (Part 10, H.264/AVC) leads to random interdeparture times of video packets from the video buffer. In order to minimize the initial waiting time before the video playback starts at the user terminal, the goal is to use the minimum buffer load size which guarantees the target probability of interruption under the particular delay jitter.

To evaluate the video interruption probability, a simple asymptotic method has been presented for the case in which the video length approaches infinity. However, in many practical cases the video length is limited, hindering the usage of the asymptotic method. We obtain a simple and closed-form upper bound for the analysis of the interruption probability that incorporates the effect of finite video lengths with known statistical

delay parameters. Furthermore, a useful method is presented to select between the proposed method and the asymptotic method whose relative accuracy changes with the video length and statistical properties of the buffer load size. The accuracy of the proposed analytical method is compared with the existing methods. Finally, we address some practical challenges in buffer dimensioning when the statistical delay parameters are unknown and estimated with a finite number of received packets.

### **Application of cooperative clusters for improving video streaming experience**

Cooperative and heterogeneous wireless networks have gained some interest recently to provide additional capability to improve the network performance. In this context, the network heterogeneity refers to a combination of wide-area and short-range wireless networks whereas the cooperativity indicates that the network nodes may act as a source, helper relay node, or destination. A major problem in a delay-sensitive cooperative content distribution is the route starvation effect which results from poor packet allocation among different routes. In this work, the potential gain in decreasing the probability of playback interruptions with different cooperative multiroute packet allocation protocols is evaluated.

The left-hand side of Fig. 1 illustrates a heterogeneous cooperative video streaming system. We assume that a given number of nodes in the close proximity are interested in downloading the same video content real time. Therefore, we focus on two-hop links between the source and the destination. The video transmission is performed directly from a single source node (SN) to destination-relay nodes (DRNs) which form a cooperative cluster. In the cooperative cluster, the DRNs act as decode-and-forward relay nodes to other users which have interest on the same video content. A video file is divided into packets according to a specified multiroute packet allocation algorithm. We provide new insights on how the user heterogeneity in terms of time-varying packet delays influences the possibility to cooperatively solve the user problem arising from frequent video interruptions. A possible application of the analysis is to assist the resource management to predict if the cooperation would be able to help in avoiding the interruption problem for the given network delay jitter and delay characteristics of the target video file.

### **Discussion**

In this work, we have presented a simple expression for the analysis of the interruption probability that incorporates the effect of finite video lengths. In many practical cases, one is not necessarily interested to know the exact probability of interruption but rather to know that the probability is below some set target value. Therefore, the novel theorem provides important insight on the effect of video length on the interruption probability, as it has an upper bound characteristic with a simple closed form. The relative accuracy between the proposed method and the asymptotic method changes with the video length and statistical properties of the buffer load size. Consequently, a useful selection threshold is presented to indicate which approach is superior for a particular case. Remarkably, the accuracy is significantly improved while retaining a similar complexity order as with the asymptotic method. The analysis leads to a novel composite prediction method which is demonstrated using appropriate computer simulations in a selected video streaming scenario. Our numerical study further illustrates that nonidealities related to statistical parameter estimation with a finite number of received packets may become a bottleneck and must be carefully taken into account in order to be able to trust the resulted buffer dimensioning. In the future work, the methods to reduce the sensitivity to these practical aspects will be investigated.

The potential gain in decreasing the probability of playback interruptions with different cooperative multiroute packet allocation protocols is also evaluated. The target system is constrained by the given random network delay jitter and variable rate video characteristics. The results demonstrate how the user heterogeneity and packet allocation type affect the potential benefit of using cooperative video streaming in terms of video interruption probability. It is shown, both analytically and with simulations, that in this specific but important problem, cooperating users may benefit differently from the collaboration due to the route starvation effect. The results suggest that the source node should be harnessed with a capability to predict if the cooperation is able to solve the video interruption problem of the particular user. In the future work, a higher number of cooperating nodes and the accuracy of the analytical approach will be investigated in more detail.

### **Acknowledgements**

This work was supported in part by the SANTACLOUDS and COIN projects funded by Tekes as well as AWARENESS project funded by VTT.

### **Related publications**

Antti Anttonen and Aarne Mämmelä, "Interruption probability of wireless video streaming with limited video lengths," IEEE Transactions on Multimedia, vol. 16, no. 4, June 2014, pp. 1173-1180.

Antti Anttonen and Aarne Mämmelä, "Reducing video interruption probability with cooperative heterogeneous networks," IEEE Vehicular Technology Conference, Seoul, May 2014.

## 2.4 Solutions for improved robustness of wireless multimedia communications in critical healthcare scenarios



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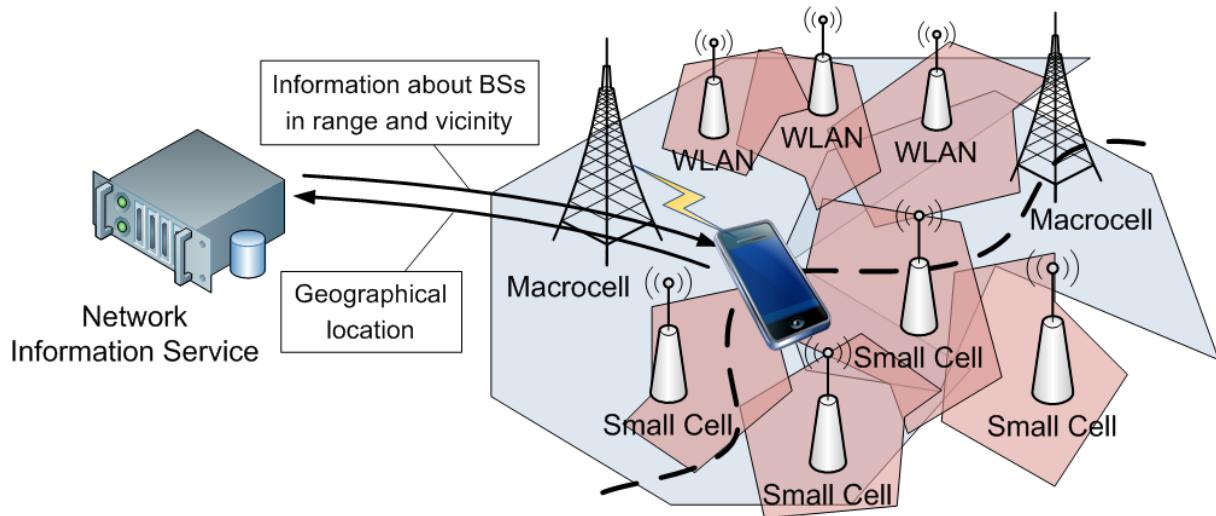
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Recent developments of broadband mobile communication, network technologies and multimedia streaming applications have enabled interesting new possibilities to build services for mobile healthcare (m-health). One of such services is real-time streaming of video from a remote or emergency area to medical experts located at the hospital to perform real-time diagnostics. By combining the diagnostic medical video content such as medical ultrasonography together with a live video feed from the emergency site, even more realistic view of the situation can be provided for the medical experts. For example, they can guide and support medical or paramedic staff during the operation regarding the first-aid actions on field or decide the most suitable hospital or department which should treat the patient when arriving to the hospital.

The reliability of communication in such critical m-health scenarios is crucial and a certain level of quality should be guaranteed also when best-effort networks are utilised for communication. VTT has developed solutions to improve the robustness of critical m-health scenarios in heterogeneous network environment. The main focus of our studies have been on first to improve the robustness of connection between the ambulance or emergency site and the hospital by developing technologies to help mobile devices or end systems discover different networks at or near their location. By utilising information about the discovered networks, it is possible to select the network(s) in terms of required Quality-of-Service (QoS). The second focus area related to the improvement of the communications robustness has been on the utilisation of several network interfaces simultaneously so that traffic can be shared among the interfaces according the available resources of the utilised networks. We discuss about these two approaches to improve the robustness in the following sections.

### Network information service concept to improve reliability of critical communication

Network information services (NIS) allow mobile end systems to discover heterogeneous networks at or near their current location. Information services have been standardized in IEEE 802.21 and in 3GPP Access Network Discovery and Selection Function (ANDSF). However, neither of the standards allows determining the coverage areas of base station cells. In order to attempt to keep up with sufficient wireless resources, the number of base station (BS) cells is expected to increase substantially and the average coverage areas of cells to decrease in future communications systems. The scanning model for discovering connection points is not efficient anymore when the number of cellular bands and IEEE 802.11 access points increase, and if multiple mobile operators share their base station infrastructure. NIS facilitates individual mobile devices to query for possible connection points in range and nearby, and possibly also their QoS. Mobile devices just need to send their current geographical coordinates to NIS in order to determine the base stations covering their location. However, the knowledge of coverage areas can be exploited in the proactive base station selection when the driving route is known. This is often the case with emergency vehicles such as ambulances. NIS enables selecting the base stations in advance, as illustrated in Fig. 1. In addition, the mobile operators could be advised to guarantee the QoS of the high priority user in the selected cells throughout the traversed path. The mobile devices to update the coverage area database are in an important role in order that the database reflects the current situation.



**Fig. 1. Network Information Service assisted mobility management.**

#### Improved reliability with multipath video streaming

Due to increased availability of wireless networks, it is very common to have multiple and heterogeneous access networks available especially in an urban area. The most typical example is that the area is covered by a cellular access network (3G/4G) and one or several Wi-Fi hotspots. The availability of several different access technologies and networks can be utilised to improve the robustness of end-user's network connection by using several access technologies simultaneously. If one of the networks available is congested or suddenly not available due to a malfunction, other networks or access technologies can be utilised to keep the end-user connected. Current mobile devices have commonly several network interfaces (typically 3G/LTE and Wi-Fi) available which makes it possible to utilise such multipath communication technologies. Multipath communication can be used easily in critical communication scenarios such as m-health scenarios to improve the robustness of critical communication between end-hosts, e.g. between an ambulance on the move and the hospital.

One of the recent extensions to one of the main communication protocols used in Internet, namely Transmission Control Protocol (TCP), is extending the usage of TCP for multipath communications. This protocol extension is called Multipath TCP (MPTCP) and it implements multipath transmission transparently to the application and MPTCP connections appear to the network as normal TCP connections. On top, the MPTCP function manages the individual TCP subflows through implementing path management, packet scheduling subflow interface, and congestion control. MPTCP also appears to the network as normal TCP connections alleviating any possible middlebox issues (e.g., firewalls) on the service availability.

The most common protocol choice for video streaming today in Internet is to use HTTP protocol due to the supporting delivery architectures (such as content delivery networks, CDN) and the wide adoption of HTTP protocol. MPTCP is seen as a natural choice for HTTP streaming, as HTTP streaming operates on top of TCP, and MPTCP essentially is a modified version of TCP that implements a multipath transport transparently to the application. In fact, MPTCP was designed to work with legacy applications through the standard TCP API. Recent advances in the field of video streaming have introduced new adaptive technologies to deliver video via IP-based networks. For example the standardized MPEG-DASH (Dynamic Adaptive Streaming over HTTP) technology enables both bit-rate and the device adaptability by generating several versions of the same media content at different bitrates/resolutions, segment these versions into short segments and dynamically download the segments of a particular version which fulfil e.g. varying network conditions. This allows to dynamically adapting the bitrate of the video according the available bitrate of currently used network in heterogeneous network environment which could be the case in the scenario of a moving ambulance. By combining dynamically adaptive video streaming with multipath delivery simultaneously, we can further improve the robustness of media transmission in critical m-health scenarios.

#### Discussion

The advances in wireless communication, computing and multimedia processing have enabled whole new ways to utilise information and communication technologies also in the healthcare. These advances enable us to

build new m-health services and products such as remote consultation of patient on an emergency site utilising both medical and supporting media content. However, the reliability and robustness of communication in such critical scenarios should be as good as possible even though networks without quality control are used. Technologies developed and proposed such as network information services, multipath delivery and adaptive video streaming can be utilised to improve the robustness and reliability of wireless communication.

#### **Acknowledgments**

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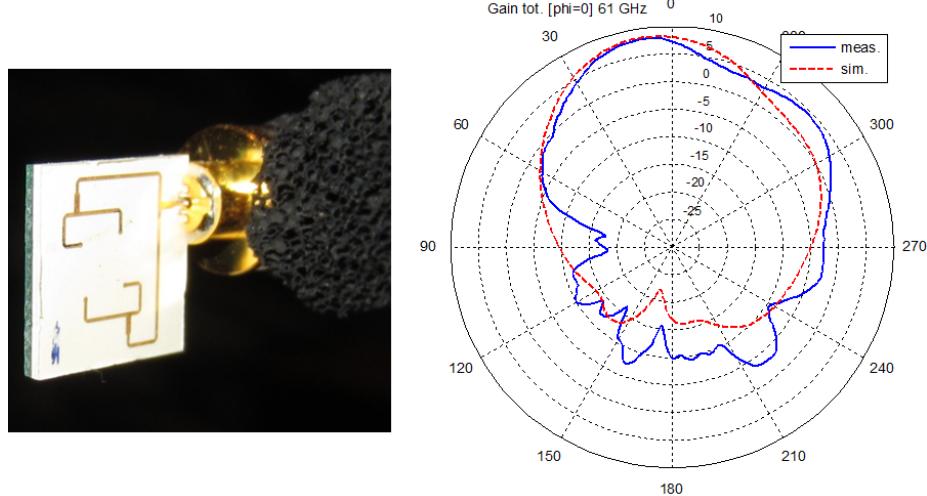
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### **3 More system capacity**

- 3.1 Licensed share access for mobile broadband**
- 3.2 Global spectrum opportunity assessment and regulation**
- 3.3 Spectrum sharing with satellite communication**
- 3.4 Reconfigurable antenna based enhancement of dynamic spectrum access algorithms**
- 3.5 Massive MIMO techniques for 5G radio access systems**
- 3.6 Millimetre wave radio technologies for 5G cellular systems**



### 3.1 Lensed shared access for mobile broadband



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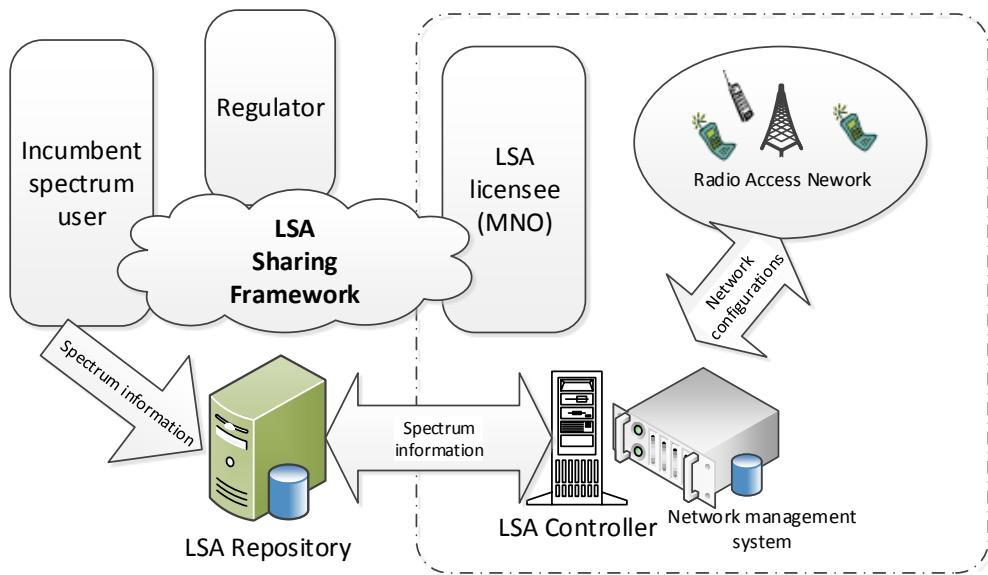
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The growing use of high traffic wireless services has led to strong mobile traffic growth. End users have got used to enjoying good Quality of Service (QoS) over the mobile broadband and the continuous traffic growth will lead to congestions in the currently available spectrum bands. New spectrum is needed for mobile broadband but is often already used by other type of existing (i.e. incumbent) wireless systems and clearing is time-consuming and costly. To meet the growing demand, spectrum sharing as the means to enable more efficient spectrum usage by allowing two or more wireless systems to operate in the same band. Spectrum sharing has moved from research phase to the development practical spectrum sharing models for specific systems in specific bands. After extensive research efforts on spectrum sharing, there is a growing number of dynamic spectrum sharing models proposed by the industry which have been moved forward to the spectrum regulation and standardization. In Europe, the Licensed Shared Access (LSA) concept has gained significant interest as a potential means for more efficient spectrum use while preserving incumbent spectrum users' rights while offering QoS guarantees for the entrant system as well.

#### LSA concept and its development

The LSA concept was initially introduced by the European Commission (EC) in [1] based on an industry initiative for spectrum sharing that aimed at allowing a mobile system to share spectrum bands with other type of incumbent spectrum users. The LSA concept [1] enables the introduction of a new radio system to a frequency band currently used by other incumbent systems based on an individual licensing scheme. It facilitates spectrum sharing with QoS guarantees for both the incumbent and the entrant systems operating in the same spectrum band which makes it appealing for practical deployment. In particular, the LSA concept could help the mobile network operators (MNOs) to respond to growing traffic demand by gaining access to new spectrum bands in a timely manner on a shared basis with other type of incumbent spectrum users. The LSA license together with the related sharing framework is negotiated between the incumbent and the new entrant, so called LSA licensee, and the license is issued by the regulator. The LSA license together with the sharing framework will allow full control over the interference and enable provision of certain QoS to all users. The 2.3-2.4 GHz band is being studied as the first use case for LSA in Europe. There are already developments in both regulation [2] and standardization [3] on the LSA concept.

When applied to the mobile broadband, the LSA concept could offer fast access to new spectrum utilizing the existing cellular network infrastructure and a limited number of new components for the LSA spectrum availability information exchange and network reconfigurations. In practice, the LSA concept requires two additional functional elements on top of the existing cellular network infrastructure to support the varying LSA spectrum availability and for the preservation of the rights of the incumbent users. Firstly, a database (LSA Repository) is needed for storing and updating the information about the availability and use of LSA spectrum together with operating conditions to guarantee that the incumbents are protected from harmful interference. Secondly, a management unit (LSA Controller) within the MNO domain is needed to configure the network according to the varying LSA spectrum availability by granting permissions within the mobile network to access the LSA bands based on the information and policies provided by the database. Figure 1 illustrates the stakeholders and key building blocks of LSA.



**Fig. 1. Key stakeholders and elements in LSA concept.**

#### Pioneering LSA trial work in Finland

Finnish CORE+ project [4] coordinated by VTT showed the world's first live field trial of the LSA concept in the 2.3-2.4 GHz band in 2013 and documented in [5]. The trial showcased the feasibility of the LSA concept for spectrum sharing between long-term evolution (LTE) and programme making and special events (PMSE) systems in the 2.3 GHz band in Finland. The LSA trial was continued with five new public LSA trials with enhanced features in research, standardization and industry forums in 2013-2014, see Figure 2. The unique Finnish LSA trial implementation consists of commercial LTE network equipment in the 2.3 GHz band as well as LSA specific components developed for the trial including LSA Repository and LSA Controller. The LSA implementation has taken into account the requirements from regulation, business and technology domains and is aligned with standardization efforts. In order to evaluate the performance of the LSA concept, times scales required by the LTE network to release the LSA band on-demand when the incumbent requests have been analysed. The LSA implementation showcased the feasibility of the LSA concept for the mobile broadband as a natural evolution of cellular mobile communication systems. In addition, 13 of scientific publications were prepared in the leading forums (see e.g. [6] [7]) and ten contributions to spectrum regulation were done.



**Fig. 2. Finnish LSA trial demonstration.**

## Acknowledgement

This work was done in CORE+ project [4] in Tekes Trial program in collaboration with WISE2 project.

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### 3.2 Global spectrum opportunity assessment and regulation



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The availability of sufficient amount of spectrum for different wireless services, such as the mobile broadband, is a key driver of global economic growth. The availability of new spectrum to meet the growing demand of different services, however, is constrained by the lack of unallocated spectrum. The actual day-to-day usage of the spectrum bands can have significant variations being e.g. concentrated on specific locations, times and frequency bands which leaves room for improvement for the overall spectrum usage. In particular, there is an emerging spectrum shortage in the high population density areas which experience a rapidly increasing use of mobile broadband services whose use is from commercial cellular systems into e.g. public safety domain. An important tool to understand and assess the current spectrum usage is to conduct spectrum measurements which can be used to assess current status of spectrum use and the availability of spectrum for shared use taking advantage of cognitive radio system (CRS) techniques.

#### Spectrum occupancy measurement and modelling

Spectrum occupancy is a metric to assess the efficiency of the current use of the radio spectrum. Spectrum occupancy measurement studies aim at quantifying the proportion of time that a certain frequency channel or a frequency band is occupied in a given area describing the utilization rate of the band based on measurements of the radio spectrum. In general, the aim of spectrum occupancy measurement and modelling activity is to collect measurement data over the spectrum bands of interest, process the data to estimate the spectrum occupancy and possibly other metrics, and develop models to characterise and predict the spectrum use. This information could help regulators about the efficiency of current use of spectrum allocations as well as industry to develop more efficient resource management techniques.

The GlobalRF project collected spectrum measurements at geographically dispersed, temporally coordinated RF spectrum observation sites in Chicago, US, and Turku, Finland, using the measurement setup described in [1]. The project evaluated the spectrum occupancy in the 2.3-2.4 GHz band which is currently under study in European regulation and standardization for the possible shared use by mobile communication systems and incumbent systems under the Licensed Shared Access (LSA) concept. The analysis of the spectrum occupancy measurements conducted in the project in the 2.3-2.4 GHz band in Turku, Finland, presented in [2] indicate that the use of this band is rather low and there might be potential for mobile communication systems to share this band with the incumbents under the LSA approach.

Measurement data can be used in deriving models to characterize the spectrum occupancy of existing systems. In fact, the development of accurate models for current spectrum users' behaviour becomes essential when exploring potential spectrum opportunities for spectrum sharing. GlobalRF project developed a non-stationary hidden Markov model (NS-HMM) for the modelling of current spectrum users' behaviours in [3]. The derived algorithm was applied to the problem of channel state prediction in CRS networks. Through experiments based on real spectrum measurement data, the proposed work showed convincing performance gains.

#### Spectrum sharing regulatory developments

There are several spectrum sharing models under development in the spectrum regulatory domain as we have reviewed in [4] with a focus on recent European and US regulatory developments. As the spectrum regulators have the key role in defining rules and conditions for sharing, we derived regulators' criteria for successful sharing models in [5] and presented a comparison of the recent European LSA model and US Spectrum Access System (SAS) model against these criteria.

The United Nations based International Telecommunication Union Radiocommunication sector (ITU-R), which globally deals with spectrum matters, recently completed its report on the application of cognitive radio systems (CRSs) in the land mobile service [6]. The work was chaired by VTT and several contributions were done in CORE+ and GlobalRF projects. The report continued the work of [7] that introduced CRS technology in the land mobile service. The developed report [6] identifies horizontal spectrum sharing and vertical spectrum sharing cases where vertical refers to the case where radio systems with CRS capabilities share the band of another radio system as long as the other radio system is not affected, while horizontal denotes the case where radio systems with CRS capabilities are accessing the same shared spectrum band. CRS technologies were seen as an enabler for spectrum sharing and radio resource management on a more dynamic basis providing increased spectral efficiency and mitigating the problem of congestion. The report presents existing, emerging and potential applications employing CRS capabilities and the related enabling technologies, including the impacts of CRS technology on the use of spectrum from a technical perspective. It also provides high level characteristics, operational and technical requirements related to CRS technology, their performances and potential benefits and factors related to the introduction of CRS technologies and corresponding migration issues.

### Acknowledgement

This work was done in GlobalRF project in WiFiUS virtual institute in collaboration with Turku University of Applied Sciences, University of Oulu, Illinois Institute of Technology (US) and Virginia Tech (US) and CORE+ project in Tekes Trial program.

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### 3.3 Spectrum sharing in satellite bands

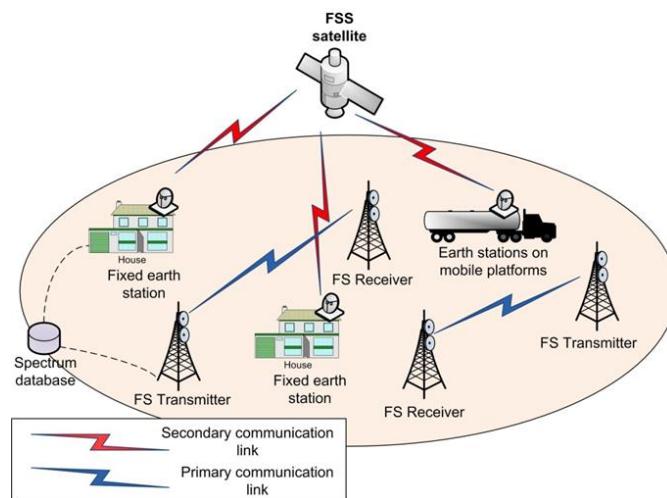


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Previous sections [3.1](#) and [3.2](#) already gave good justifications for spectrum sharing in general. Terrestrial systems nowadays are already using different kind of frequency sharing techniques to increase the efficiency of spectrum use, including Carrier Sense Multiple Access (CSMA) and Coordinated Multi-Point Transmission and Reception (CoMP). In addition, during the last decade there has been active research work going on in the development of sharing techniques that would allow coexistence of several systems in the same band. The main focus has been in terrestrial side and only limited effort has been put on the satellite bands. Due to ever increasing demand of capacity, satellite bands also need to be used as efficiently as possible to be able to provide required services to the end users, and consequently the bands might need to be shared among several applications. Licensed shared access (LSA) is emerging as a promising candidate for several different bands. LSA and other spectrum database approaches are favourable in satellite bands as well since they provide better protection to incumbents than spectrum sensing approach.

#### Sharing in satellite bands

Even though dynamic frequency sharing techniques have been studied intensively for terrestrial systems during the last decade there are still several challenges related to application of those techniques in satellite systems. Indeed, satellites systems are different from terrestrial systems at least for the following reasons: 1) Signal levels are magnitudes smaller and thus, highly directional antennas are needed instead of omnidirectional ones that are typical in terrestrial systems. 2) Cell size or beam coverage of a satellite is magnitudes larger, thus the potential for aggregate uplink interference is high. 3) Propagation delays are much larger due to longer links. 4) Finally, infrastructure flexibility is very limited and usually in-orbit hardware upgrades are not possible. This means that careful redesign is needed for techniques developed in terrestrial domain to be well applicable in satellite systems. VTT is developing sharing techniques in collaboration with Finnish and International companies taking into account technical, economic, and regulatory viewpoints to find best solutions for satellite bands.



**Fig. 1. Spectrum sharing scenario where a secondary fixed satellite services (FSS) system accesses the band used primarily by a terrestrial fixed services (FS) system.**

An important part of the work is the definition of suitable scenarios. Basically the sharing can be classified to four different categories as 1) Secondary use of satellite spectrum by a terrestrial system, 2) Secondary use of terrestrial spectrum by a satellite system that is depicted in Fig. 1, 3) Collaborative transmission over satellite and terrestrial links, i.e., co-primary satellite and terrestrial systems and 4) Spectrum sharing between satellite systems. Each scenario requires different techniques to be used in order to enable efficient sharing of the spectrum. For example, in the case shown in Fig. 1 the spectrum database, location information, and directional antennas seem to be a promising combination. Spectrum access using the database is depicted in Fig. 2. The satellite operator uses the database to be able to decide whether it is possible to use the shared spectrum at certain location and what the restrictions for the operation would be.

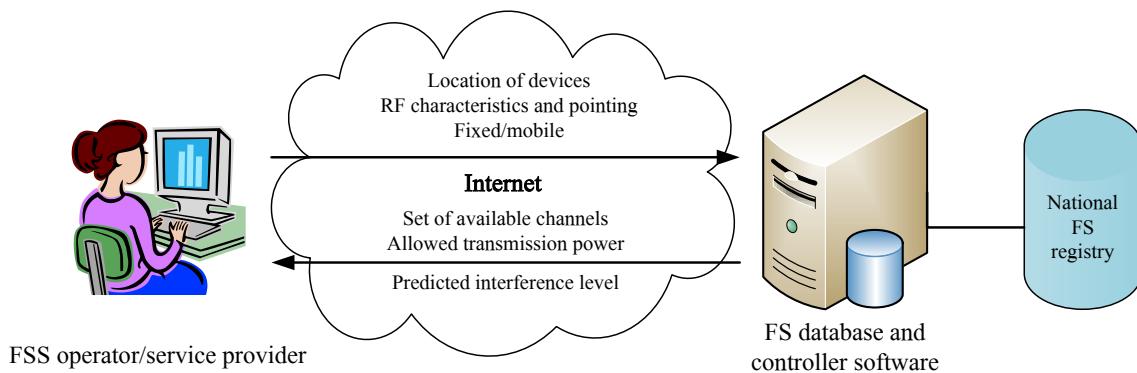


Fig. 2. Database based access for satellite services in Ka band.

### Roadmap for the future

Based on our own research work and development of techniques in each scenario we have been able to identify the most promising scenarios, frequency bands, and systems that would gain most from spectrum sharing. In addition, knowledge of possible techniques and challenges in each scenario helped in identifying critical services where sharing the spectrum should be avoided. An important part of the current work is the definition of a roadmap that will identify further research and development needs and provide justification for investments. The roadmap defined in the project together with the satellite industry will have an effect on future activities and funding in European level.

### Discussion

Based on current understanding there is lot of potential capacity available in satellite bands when suitable frequency sharing techniques are used to access it. In addition, satellite systems can access terrestrial frequencies e.g., in Ka band to increase their capacity. There has been fear and objection from several stakeholders to include any shared users in satellite bands due to interference that might block current use. However, studies such as our own shows that with careful planning frequency sharing is possible. Also satellite systems can gain in this situation and be able to provide reliable communication to end users in a sharing scenario when proper techniques are used.

### Acknowledgments

Discussions with Maria Guta (European Space Agency) and Ari Hulkko (Elektrobit) are acknowledged.

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### 3.4 Reconfigurable antenna based enhancement of dynamic spectrum access algorithms



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#### Introduction

The future increase of wireless systems and services is dependent on the design of flexible radio architectures that can adapt to the rapidly changing wireless environment. Since usable spectrum is limited, and modulation and coding techniques are approaching their Shannon capacity limitation, improving capacity through increased spectrum reuse and interference mitigation has become a high priority in future cellular networks. In a dense wireless network where wireless system performance is constrained heavily by the interference footprint of nearby users, antennas are one of the final tools that a designer can exploit before transmitting signals into the wireless channel. In this regard, adaptive antenna systems represent a significant element of design for enhanced small-cell deployment. These kinds of adaptive antenna systems can enable extension of transmission range, increase of data throughput, enhance spectrum reuse, and substantially reduce co-channel interference which is one critical issue in future heterogeneous wireless communications systems where classical macro networks and more advanced small cell systems are coexisting. Recently, these advantages of adaptive antenna systems are also clearly acknowledged in both academia and industry, e.g. by all major network and device vendors (e.g. Samsung and NSN), and are also gradually building into emerging standards as well.

Adaptive antenna systems can steer the main beam in a desired direction and spatial nulls in undesired directions to avoid interference. A wireless device has to acquire direction-of-arrival (DoA) information to steer the beam in the required direction. Thus, DoA estimation algorithms have played an important role in the practical exploitation of adaptive antenna arrays. In addition to spectrum reuse and interference avoidance, estimated DoAs can be used for transmitter localization.

#### DoA estimation algorithms using compact CRLH leaky-wave antennas

Adaptive antennas can be classified into two classes: 1) phased arrays, and 2) reconfigurable antennas. In phased array systems, the beam direction and radiation pattern shape is controlled by using an array of many elements, resulting in very large form factors, e.g., at WiFi frequency range of 2.44 GHz - 2.46 GHz. Due to these form-factor limitations, conventional phased arrays and associated steering techniques are more feasible to deploy in the case of large base station devices. In contrast to large traditional antenna arrays, the class of composite right/left-handed (CRLH) reconfigurable leaky wave antennas (LWAs) do not require multi-element antenna arrays or feeding networks. Additionally, LWAs have also many other benefits: low manufacturing cost and low DC power consumption, full-space beam scanning using considerably less printed circuit board space, and absence of extra radio frequency (RF) circuitry. By considering these benefits, particularly compactness and beamsteering, CRLH-LWAs have a great potential to be used in DoA systems.

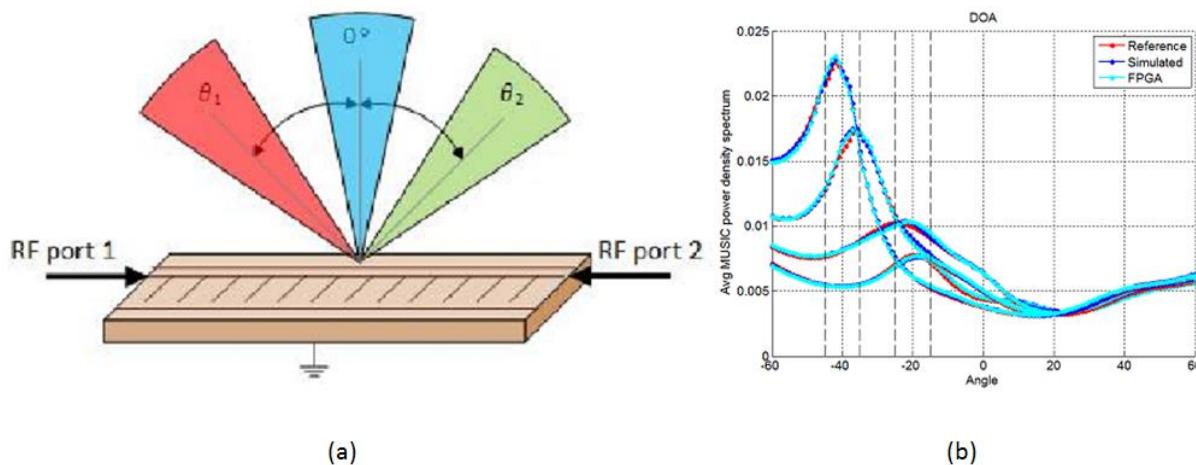
The traditional antenna array algorithms cannot be directly used for DoA estimation and beamforming using CRLH-LWAs due to the inherent difference in design and operation of the LWAs versus conventional antenna arrays. The reason for this difference is that only a single observation is available at each sampling instance, unlike conventional antenna arrays where signals from all the elements can be observed at the same time. For example, the conventional multiple signal classification (MUSIC) algorithm generates a spatial correlation matrix of the signal samples received from the elements of an antenna array. When LWAs are used, the conventional MUSIC algorithm is no longer directly applicable. Therefore, single/two-port MUSIC algorithm uses  $M$  received signals from  $M$  different directions that are measured from two antenna ports and a spatial correlation matrix can be formed by using these  $M$  received signals, as discussed preliminarily in [1].

In our work, we have studied novel algorithms which use two antenna ports at the same time. We also take the advantage of the beam symmetry characteristic of LWAs by using both antenna ports at the same time and by

steering bi-directional beams, as illustrated in Figure 1 (a). As a result, the overall signal acquisition and estimation time is halved, and the length of the periodical training sequence can be truncated. Additionally, the algorithms can be used in multiple input multiple output (MIMO) systems. In our research, we have analyzed the experimental performance of three novel DoA estimation algorithms with a two-port CRLH-LWA:

- single/two-port MUSIC
- single/two-port unitary MUSIC
- power pattern cross correlation (PPCC).

Additionally, the relative performances of these three algorithms are qualitatively compared to a low-complexity power detector. Preliminary studies for the proposed MUSIC algorithms are introduced in [1 - 3]. The papers [1 - 3] present the performance of the single/two-port MUSIC algorithms in an anechoic chamber. In papers [4-5], we introduce the measurement results of DoA estimation in a multi-path indoor environment, conducted in a large lobby area at Drexel University. Additionally, the unitary MUSIC algorithms for LWA have been implemented and validated on field-programmable gate array (FPGA) and integrated into the EBRACE software defined radio (SDR) platform. Figure 1 (b) illustrates an example of results from the anechoic chamber measurements for the single/two-port unitary MUSIC algorithms computed with original and implementation-optimised software models (red and blue curves) and FPGA hardware (cyan curve).



**Fig. 1. (a) Sketch of a two-port CRLH leaky-wave antenna and (b) DoA estimation results for the single/two-port unitary MUSIC algorithms.**

### Acknowledgments

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### 3.5 Massive MIMO techniques for 5G radio access systems

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#### Need

Multiple Input Multiple Output (MIMO) techniques are one of key technologies in 5G systems [1]. The main idea is to use the multiple antennas at a transmitter and receiver to improve the performance of wireless communication systems. The MIMO techniques are very effective to mitigate the degradation of fading channels and enhance the link quality between a transmitter and a receiver. Especially, it significantly improves spectral efficiency and error probability. The MIMO techniques are classified into spatial diversity techniques, spatial multiplexing techniques and beamforming techniques. Each technique targets to improve different aspects of wireless communication system performances.

Massive (or Very Large) MIMO techniques use more than 100 antennas. This technique has a big potential. A massive MIMO technique can increase 10 times or more channel capacity and improve 100 times or more energy efficiency [2]. In massive MIMO systems, a bigger size of channel matrix must be estimated. This is one big problem of a massive MIMO system. In high frequency bands, antenna elements can be very small and it is possible to use very large number of antenna element. Thus, we can produce a very narrow beam meaning that a massive MIMO technique is well matched at a high frequency technique such as millimeter wave (mmWAVE) techniques. In addition, the performance of MIMO systems depends on channel correlation. There are two types of channel correlation. The first one is spatial correlation. In practical MIMO system, each MIMO channel is related to another channel with different degrees. It depends on multipath channel environment. The second one is antenna mutual coupling. Antenna mutual coupling is caused by the interaction among transmit antennas. This effect becomes very serious problem if antenna spacing is very small like in a massive MIMO system. Massive MIMO techniques should overcome channel correlation problems.

#### Approach

In 5G systems, the system capacity can be improved by 3 different ways: Bandwidth increase, Spectral efficiency increase and Frequency reuse. Table 1 summarizes the technologies for capacity improvement. In order to improve system capacity, we take the second approach. More specifically, we focus on massive MIMO techniques.

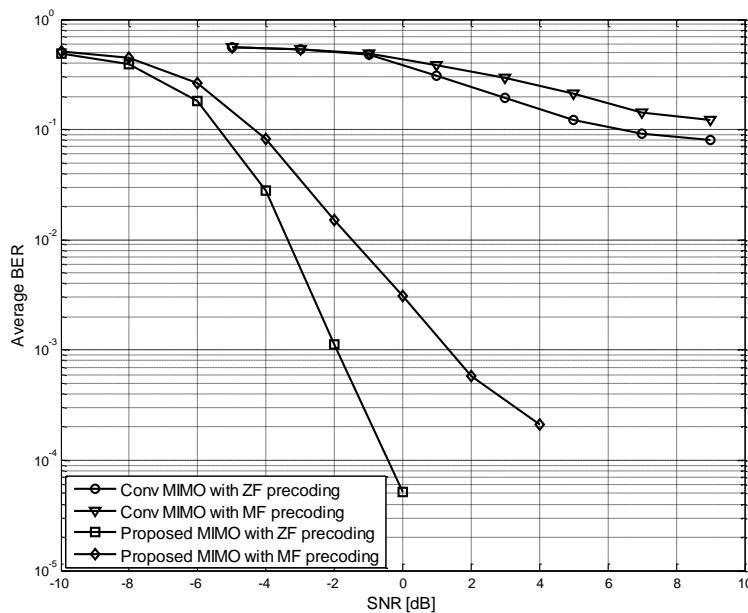
As we can observe in the second approach (spectral efficiency increase) of table 1, the MIMO technique allows us to achieve the very high system capacity when increasing the rank of correlation matrix. Namely, a higher number of MIMO antennas mean a higher spectral efficiency. However, the required conditions of the massive MIMO technique are (1) accurate channel matrix estimation, (2) channel correlation and antenna mutual coupling overcome, and (3) low complexity implementation. We deal with these problems.

#### Research topics and results

A new massive MU-MIMO technique with Discrete Fourier Transform (DFT) spreading for antenna mutual coupling and interference has been investigated. The key idea of the proposed scheme is to use the DFT spreading technique in the transmitter [3]. The DFT has several important properties. The first property is orthogonality which separates symbols without any interference. The second is to spread symbol energy in different domain (for example, frequency domain to time domain). The third is to preserve symbol energy after spreading. Among these properties, the second property (spreading property) is focused in the proposed system. This property is very useful to prevent a burst error. So, it is helpful to overcome an antenna mutual coupling and narrowband interference. Figure 1 illustrates the performance comparison of proposed massive MIMO schemes and conventional massive MIMO schemes under an antenna mutual coupling and narrowband interference environment. Further details are described in [3].

**Table 1. Capacity improvement in 3 different ways.**

	Technologies	Capacity ( $C$ )
Bandwidth increase	Carrier aggregation (CA), mmWAVE, Cognitive radio, etc.	$C = W \log_2(1 + SNR)$ where $W$ and $SNR$ are bandwidth and signal to noise ratio. <b>W increases.</b>
Spectral efficiency increase	MIMO, AMC, OFDM, Coordinated MultiPoint (CoMP), Interference management and traffic adaptation, etc.	$C = \sum_{i=0}^{r(\mathbf{R})-1} \log(1 + \rho \lambda_i(\mathbf{R}))$ where $\mathbf{R}$ is sum correlation matrix, $r(\mathbf{R})$ is the rank of $\mathbf{R}$ , $\lambda_i(\mathbf{R})$ is the nonzero eigenvalues of $\mathbf{R}$ , and $\rho$ is SNR. <b><math>r(\mathbf{R})</math> increases.</b>
Frequency reuse	Sectorization, Small cell, Software defined network (SDN), etc.	$C = W \sum \log_2(1 + SNR)$ <b>Number of cells/sections increases.</b>



**Fig. 1. Comparison between the proposed massive MU-MIMO and the conventional massive MU-MIMO with 64QAM and 128 transmit antennas**

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- [2] E.G. Larsson, F. Tufvesson, O. Edfors, and T.L. Marzetta “Massive MIMO for Next Generation Wireless Systems,” submitted to IEEE Comm. Mag., <http://arxiv.org/abs/1304.6690>.
- [3] Haesik Kim, “Massive Multi-User MIMO using DFT spreading for antenna mutual coupling and interference,” International Conference on Information and Communication Technology Convergence (ICTC) 2014, Busan, S. Korea, Oct. 2014.

### 3.6 Millimetre wave radio technologies for 5G cellular systems

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#### Radio frequency bands

Significant increase in throughput, capacity and energy efficiency are expected in the next generation 5G cellular networks. Although many advanced techniques can be used to partially achieve these targets, it is clear that more radio spectrum is also required. Additional radio spectrum would be available at millimetre wave frequencies from 30 GHz to 300 GHz. During the past 15 years or so, the unlicensed spectrum from 57 GHz to 64 GHz has been planned and specified for the short-range wireless local area networks (WLAN) (ECMA-387, IEEE 802.11ad and IEEE 802.15.3c). Even though the 60 GHz frequency band has been considered also for the cellular networks, it is more likely that it will be utilised only in some form of offloading. Instead, licensed frequency bands are preferred. Recently, the most interest has been in 28 GHz, 38 GHz, 71 GHz to 76 GHz, and 81 GHz to 86 GHz frequency bands. However, also the higher band from 92 GHz to 95 GHz has been recognised as an option.

#### Utilisation in 5G cellular radio systems

Millimetre wave radios are expected to play a vital role in providing very high data rate access connections in a small cell configuration. The small cell access points will be connected efficiently together and further to macro base stations with a mesh type wireless mm-wave backhaul network. The wireless backhaul links are envisioned to operate at 71 GHz to 76 GHz and 81 GHz to 86 GHz frequency bands. In the connections between the access point and the user, maximum data rates up to a few Gbit/s are targeted. In the backhaul links the data rates will be even higher up to 10 Gbit/s.

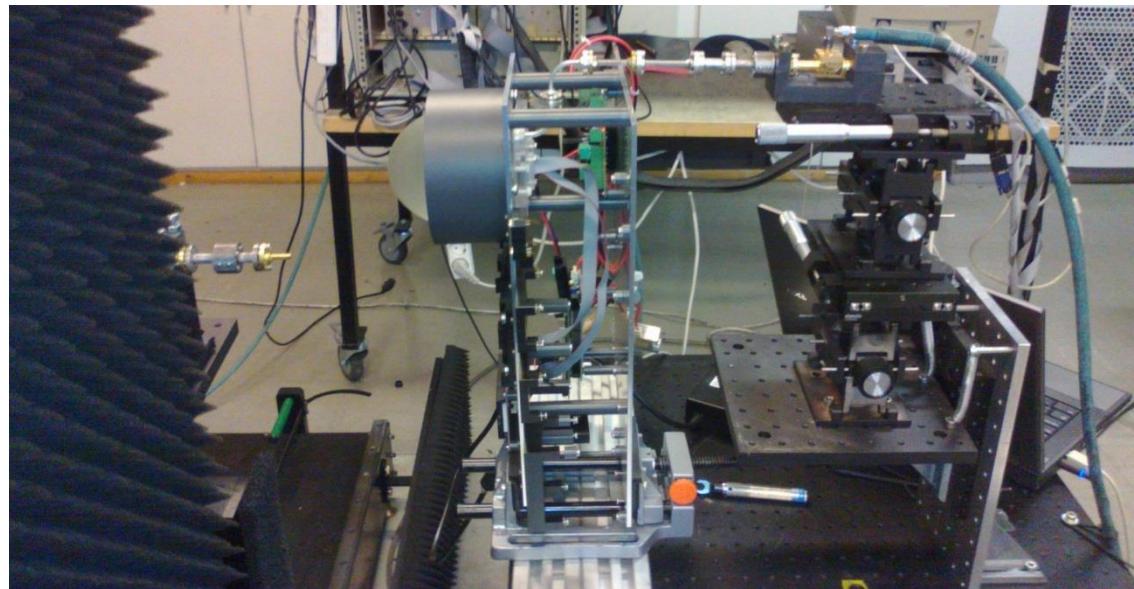
#### Results in BEAMS project

In “Beam-steering radio for applications in millimetre wave frequency bands (BEAMS)” project we continued to develop the mm-wave radio techniques and technologies foreseen in 5G cellular systems. The project, which was mainly funded by Tekes, was carried out in close cooperation with Aalto University in 2011 to 2014. During the project, we designed and assembled several mm-wave radio transmitters and receivers. Our purpose was to demonstrate the feasibility of the current technologies to several application areas including the wireless backhaul link at 71 GHz to 76 GHz frequency band for cellular base stations (Fig. 1) and short-range radios (Fig. 2) and radars (Fig. 3) at 60 GHz frequency band. We utilised the existing commercial or semi-commercial radio transceivers and other components in our demonstrations as much as we could. However, we also designed our own SiGe vector modulator (71 GHz to 76 GHz frequency band) (Fig. 4) and different mm-wave antenna solutions (antenna elements, feed arrays, Rotman lens) (see two examples in Fig. 5). In addition to beam-steering based on switching feed network, we designed a hybrid FPGA/MATLAB beam-forming demonstration setup based on the use of a low frequency vector modulator (Fig. 6). Laboratory testing, device and circuit on-wafer measurements constituted an important part of the work (Fig. 7). Additionally, Aalto University contributed e.g. in CMOS MMIC circuit designs (100 GHz to 130 GHz frequency band), conformal antenna array design, design and fabrication of lens antennas, and radio channel measurements at 73 GHz in an urban environment. The technical results of the project were reported in about 20 scientific publications.

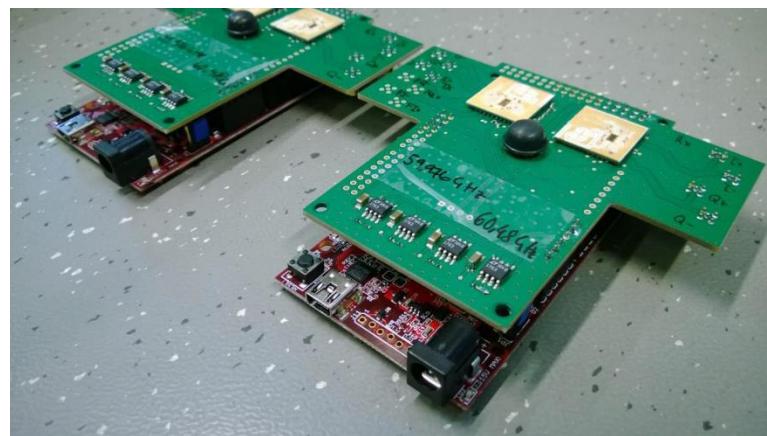
#### Example publications and reports in BEAMS project

J. Ala-Laurinaho, M. Hiivala, J. Holmberg, P. Järvensivu, M. Kantanen, D. Karaca, A. Karttunen, M. Lahdes, M. Lahti, A. Lamminen, D. Parveg, V. Semkin, J. Säily, A. Vahdati, and M. Varonen, “Beam-steering radio for applications in millimetre wave frequency bands (BEAMS),” Final report, VTT-R-00732-15, 2015.

M. Kantanen, J. Holmberg, and T. Karttaavi, “Two-way vector modulator SiGe MMIC for millimeter-wave phased array applications,” in *Proc. 8th Global Symposium on Millimeter-waves (GSMM 2015)*, Montreal, Canada, 25-27 May 2015.



**Fig. 1. Beam-steering radio transceiver with lens antenna and 2D feed array during the near-field antenna measurements.**



**Fig. 2. Short-range 60 GHz radio transceivers.**



**Fig. 3. Frequency modulated continuous wave (FMCW) radar demonstration with Infineon's RX/TX chip on LCP platform.**

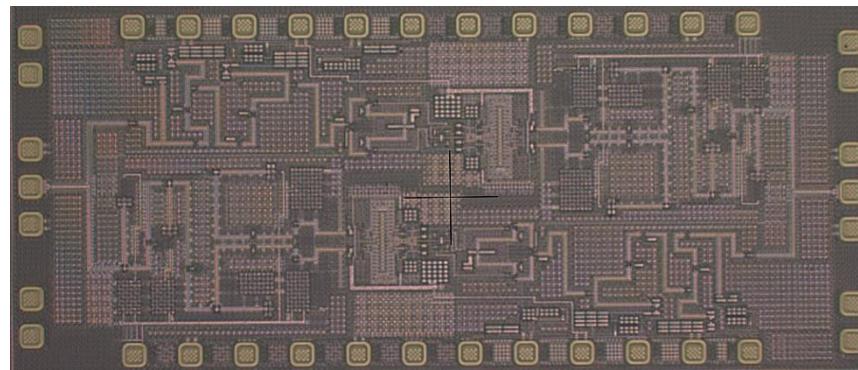


Fig. 4. Micrograph of two-way vector modulator SiGe MMIC. Chip size is 2300  $\mu\text{m}$  x 950  $\mu\text{m}$ .

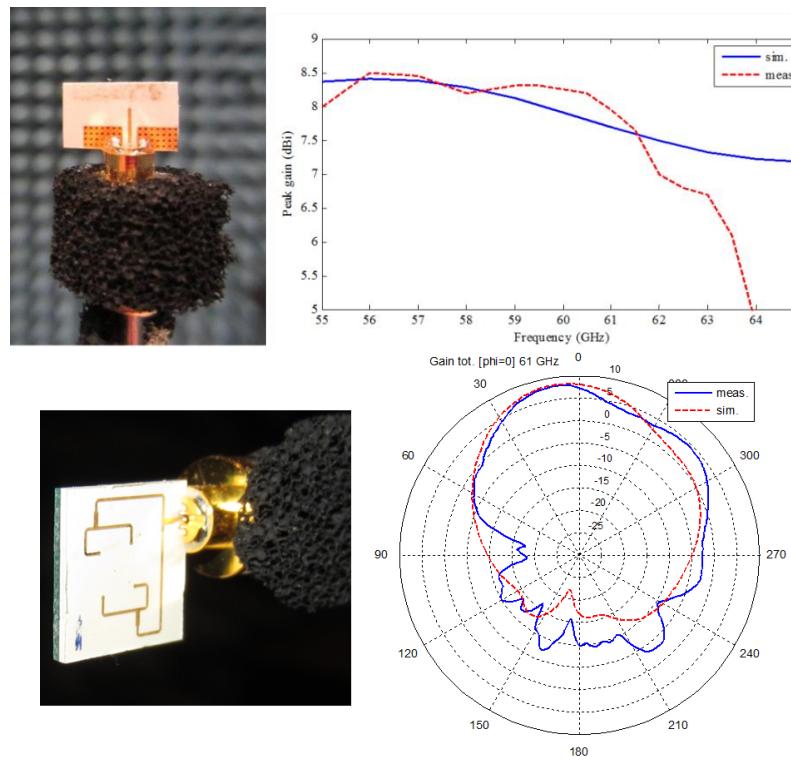


Fig. 5. 60 GHz Vivaldi (up) and circular-polarised patch antenna array (down) on LCP.



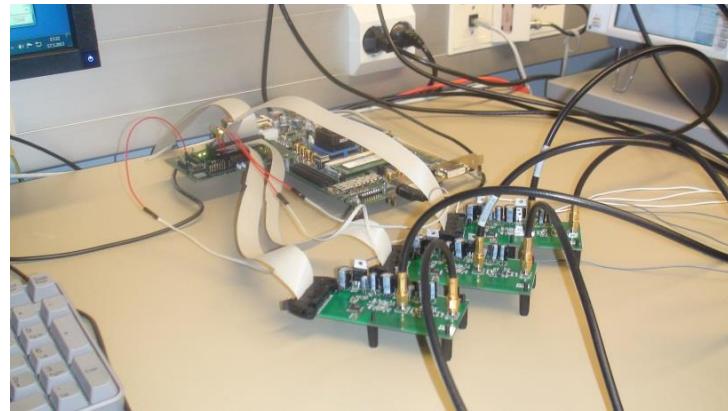


Fig. 6. Beam-forming demonstration setup in laboratory environment.

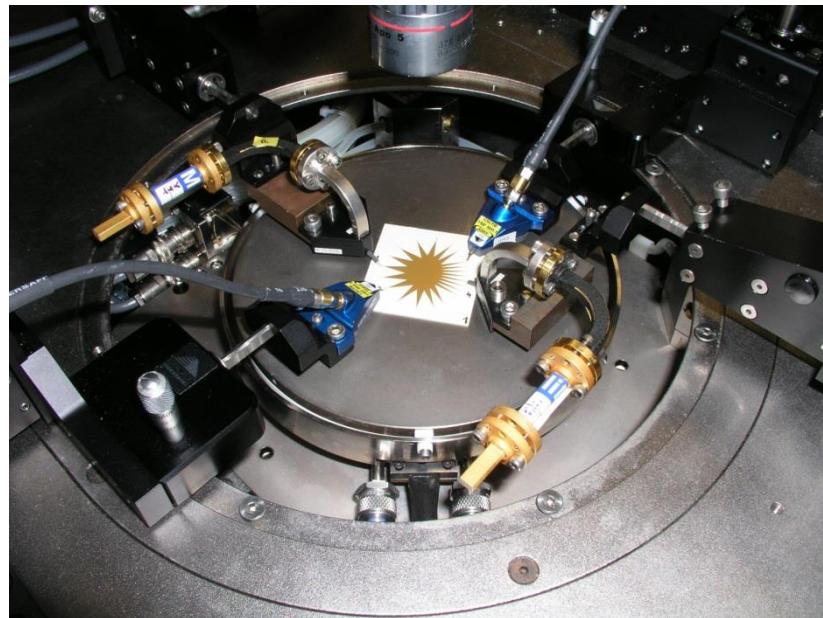


Fig. 7. On-wafer probe measurement of the 60 GHz Rotman lens at VTT.

## **4 Energy efficient solutions for radio access**

- 4.1 5G will be our joint effort**
- 4.2 Learning for optimising energy efficiency**
- 4.3 Energy-efficient radio resource management for distributed antenna systems**
- 4.4 Energy efficient basestation transmission**



## 4.1 5G will be our joint effort

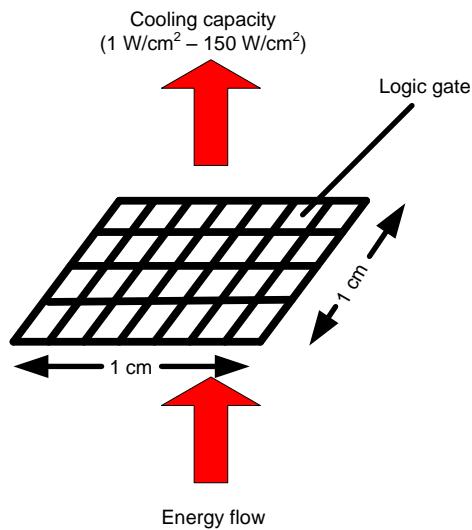


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### Thermal noise death of Moore's law

Gordon Moore defined in 1965 and refined in 1975 an exponential "law," which has been named according to him. The law is not a natural law but a prediction that follows observations on cost-efficient chips. The prediction is based on the miniaturization trend. The energy efficiency of a transistor and a logic gate has improved by a factor of one hundred in ten years, corresponding to a factor of two in 18 months. This trend has been valid since the 1950s. We have now 1 billion transistors on a chip, consuming 100-200 W. Human body consumes about 100 W of which 20 % or 20 W is used by our brain although the mass of the brain is only 2 % of the body. Thus we can expect that smart devices such as cognitive radios also consume much energy.

Exponential trends cannot continue forever. Moore's prediction is already slowing down and will come to an end in the beginning of the 2020s at the time when 5G mobile cellular systems will be taken into use. The switching energy is approaching the thermal noise spectral density. The minimum possible line width is expected to be 5 nm, which corresponds to about 20 silicon or copper atoms. In addition to noise, also leakage currents and interconnects with high capacitances will form a problem. Our designs will be resource-limited. For example the cooling capacity in terms of energy/(time x area) will form a bottleneck (Fig. 1). This will cause an energy-time-space trade-off. If computing speed is made faster (time unit smaller), the space must be increased, otherwise the energy density will be too large. Many systems are power-limited already now. The maximum cooling capacity is  $1-150 \text{ W/cm}^2$  depending on the cooling method and this is not expected to increase. Human body has a cooling capacity of  $0.01 \text{ W/cm}^2$ . The capacity of batteries will increase only by a factor of 1.5 in ten years. The greatest adventure of our time regarding the development of electronics will be over since Moore's law will undergo a thermal noise death.



**Fig. 1. All operations need energy that is changed to heat and must be removed from the chip, which will cause an energy-time-space trade-off when Moore's law will undergo a thermal noise death.**

Some alternative technologies have been proposed. We could lower the temperature but this would consume more energy than it would save. We could use error correcting codes to fight against errors caused by the

thermal noise, but they are not energy efficient in this case. Quantum computers are not a replacement of general purpose computers, but they are useful in some special problems where exponential time can be changed to polynomial time. Reversible processing has been proposed but there are doubts about its practicality. Possibilities to energy cycling are limited since energy tends to be changed into heat and radiation, which are not easy to reuse.

### Towards 5G systems

The first generation cellular systems started their operation in the beginning of the 1980s. A new generation has been introduced every ten years. The bit rates have grown exponentially. Now it is expected that the bit rates will be in the order of 10 Gbit/s, which corresponds to 3D streaming video that is downloaded at a 100-fold higher bit rate. Scalability will be obviously a must so that different applications use different bit rates and not all systems are expected to work at the highest rate.

Old design problems include high attenuation and fading, distortions, interference, and nonlinearities. These problems must be attacked with finite basic resources that include materials (silicon, copper, etc.), energy (power), time (delay), frequency (bandwidth), and space (volume, area). Especially energy will be a bottleneck since the lowest level energy efficiency cannot be improved any more. Almost all electronics is based on complementary metal-oxide-semiconductor (CMOS) technology. Digital signal processors (DSPs) follow the same "law" since each digital operation or instruction requires about 10000 transistors. If the energy efficiency of the transistors does not improve, DSPs will also saturate. Analog-to-digital converters (ADCs) will form a bottleneck since they require an energy equivalent to 100000 gates at 10 bits and 90 nm. All interfaces between chips will consume much energy since the loading capacitances are 100-1000 times larger than within the chip.

### Discussion

In the future all the layers of a communication system must work together, including services, networks, and links. They all have a functional (behavioural), structural (architectural), and physical level of description. In modern electronic systems most of the energy is consumed in the display, computing, and communications. We can see a communication system as a large network of CMOS gates, and our common goal is to minimize the total number of gates and their clock frequency. Energy consumption of analog parts, which are also using transistors, can be similarly estimated. Awareness of energy efficiency must be improved and this is a joint effort for all of us in all the system layers. Moore's law will no more solve our problems. We can learn much from living systems that are able to work quite close to the noise levels. The present supercomputers have a similar computing rate as our brain but still they can simulate only 1 % of the brain for 1 second in 40 minutes. For the simulation we need 8 MW whereas our whole brain needs only 20 W. Our best computers are still five to six orders of magnitude less energy efficient than the brain. If we set our requirements against the natural laws, nature will always win.

### Acknowledgments

Discussions with Hannu Heusala (University of Oulu), Antti Anttonen (VTT) and Marian Verhelst (KU Leuven) are acknowledged.

### Related publications

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## 4.2 Learning techniques for energy optimization



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Over the past decades, wireless cellular network payloads have been growing fast with the introduction of smart phones, tablet computers and other emerging mobile devices. In next generation wireless cellular networks, how to satisfy the ever increasing appetite for mobile data services and at the same time how to improve the energy efficiency (EE) will be two critical challenges faced by the network operators. However, as the complexity of network increases, the environmental status cannot be assumed to be static anymore. When considering energy optimization in a dynamic heterogeneous cellular network (HCN), which is more often the scenario in practice, it becomes extremely difficult to obtain the exact input-output function of the network. The dynamics comes from, for example, the stochastic behaviour of mobile terminals (MTs) and the ad-hoc topology of small cells. The incomplete information about the network dynamics and the incapability of complete environmental observations [1] require efficient learning techniques.

### Learning Scenarios

#### Energy Efficiency for Terminal Side

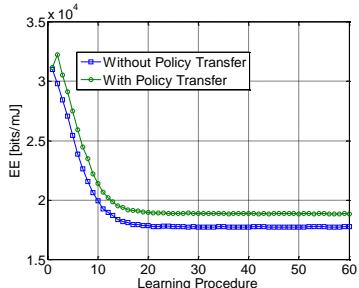
Considering the limited battery capacity, MTs care more about optimizing EE. In the scenario of spectrum-sharing HCNs, the cross- and co-tier interference greatly degrades MTs' EE performance. The existing resource allocation schemes may effectively mitigate the interference. However, the unplanned deployment of small cells in practice leads to unpredictable interference patterns, since small cells face the limited information exchange across tiers and among the same tier. It's desirable that the small cells autonomously perform interference management, which asks for a Stackelberg learning framework [7]. During the Stackelberg learning, the macro-cell base station (BS) is considered to be a foresighted leader and controls the overall interference by announcing pricing policy to the active link in each small cell. The followers are small-cell links, the objectives of which are to learn the power allocation policies that optimize their respective EE. By exploiting the temporal correlations among different learning periods, the already learned policy information can be further transferred to enhance the learning procedure [6], as depicted in Fig. 1. Therefore, the stochastic HCNs converge through properly adjusting the policies according to the realization of expected performance.

#### Energy Saving for Network Side

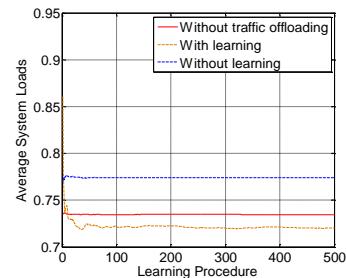
Within each cell in a HCN, the power consumption of the BS is determined by its system load<sup>1</sup>, which is coupled with the system loads in other cells due to the sharing of a common spectrum band [2] [3]. Relevant measurement campaigns show the temporal and spatial variations in traffic demands. But in practical situations, it's most probable that a priori information about the traffic variations cannot be obtained and only partial observations are available at a centralized network controller. Specifically, the network controller might know the numbers of MTs that are associated with different macro cells and small cells for a current network state. The network controller thus manages the working mode of each small cell (switched-on/switched-off) based on the system loads in different cells in order to save energy as well as to satisfy the flow-level performance for MTs [4] [5]. In this way, the network state evolves according to a controlled random process

<sup>1</sup> System load of a BS is defined as the fraction of radio resources scheduled for serving requested traffic demands from MTs, or the probability of causing interference to transmissions in other cells.

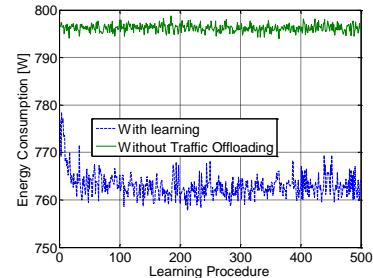
whose dynamics depend on the operations of small cells. The benefits of learning approach are illustrated in both Figs. 2 and 3.



**Fig. 1. Learning process of a MT in the small cells.**



**Fig. 2. Comparison of average system loads.**



**Fig. 3. Comparison of total energy consumption.**

## Conclusions and Discussions

The preliminary studies have shown the benefits of applying learning techniques to energy optimization problems in a small-scale stochastic HCN scenario. In next generation wireless cellular networks, the explosive increase in mobile traffic and the “tidal phenomena” of temporal and spatial traffic fluctuations will be two key challenges for mobile data services. To keep pace with the growing demands, wireless cellular network tends to be extremely chaotic and complex. Software-defined networking (SDN) is a new communication paradigm, which allows network controller to manage network services by decoupling the control plane that makes decisions about how to send traffic from the data plane that forwards traffic to the selected destinations. However, it falls short of handling large-scale cellular networks with extensive deployment of BSs. For large-scale HCNs, it becomes necessary to design a more flexible SDN-at-the-Edge type architecture. With the help of a SDN-at-the-Edge architecture [8], the energy optimization can be potentially realized for large-scale stochastic HCNs.

## Related Publications

- [1] X. Chen, Z. Zhao, and H. Zhang, “Stochastic power adaptation with multiagent reinforcement learning for cognitive wireless mesh networks,” *IEEE Trans. Mobile Comput.*, vol. 12, no. 11, pp. 2155-2166, Nov. 2013.
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### 4.3 Energy-efficient radio resource management for distributed antenna systems



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#### Introduction

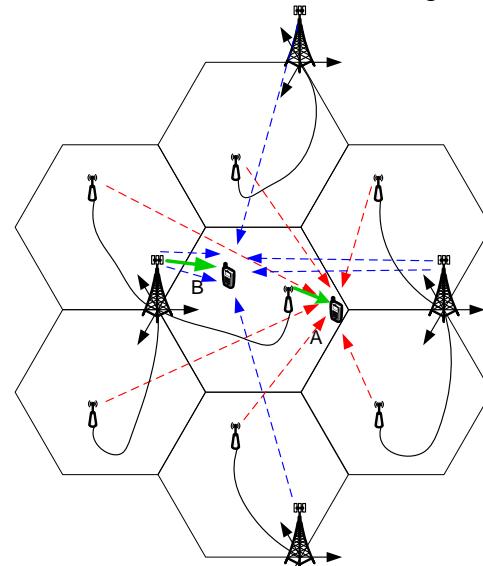
Energy consumption in cellular networks is expected to increase with the increasing wireless traffic. Currently there are over 4 million base stations globally each consuming 25 MWh per year on average [1]. Cost of energy is becoming more and more important for telecommunications operators and thus any improvement on the energy efficiency decreases the operational expenses (OPEX). In addition to reduced OPEX, energy efficiency improvements help to reduce the CO<sub>2</sub> emissions.

Distributed antenna systems with multiple remote antennas (RA) connected to a base station via dedicated optical fibers is gaining more attention as an effective means for improving the cell edge performance. This has been seen as one of the key scenarios for coordinated multi-point (CoMP) in the emerging LTE-Advanced systems. Energy efficiency was not included to the LTE-Advanced system requirements and thus several non-standard solutions have been proposed recently. Base station sleep modes, during which a base station is turned off and its previously served users are handed over to neighbouring cells, is shown to improve energy efficiency considerable under low load [2]. At a smaller scale, also individual base station antennas together with their RF circuitry can be turned off to save energy. This is enabled by discontinuous transmission (DTX) [3] that minimizes control signalling when there is no payload data to be transmitted. When the enhanced DTX is used, only the synchronization and broadcast signals are mandatory and RF circuits can be switched off for several milliseconds when there is no payload data to be transmitted. Most of the proposed energy efficiency improvements are applicable only under low load.

#### Proposed approaches

VTT participated in the Celtic-Plus OPERA-Net 2 project<sup>2</sup> whose high-level target was to reduce the overall environmental impact of mobile radio networks [4]. VTT's work in access networks optimisation focused on improving the energy efficiency of LTE-based distributed antenna systems under full load. As solutions to this problem, we have proposed 1) a dynamic point selection (DPS) and scheduling method [5] and 2) a procedure enabling downlink (DL) power control in LTE [6].

The idea of the method proposed in [5] is to combine static inter-cell coordinated antenna scheduling with the enhanced DTX. The static inter-cell coordinated antenna scheduling reduces the inter-cell interference and enhanced DTX combined with switching on/off RF chains reduces the power consumption. When the enhanced DTX is in use, it is possible to schedule the user equipments (UE)s such that all non-active antennas are put into short sleep modes. In order not to compromise the cell coverage, the sleep modes are not allowed on subframes 0 and 5 when the synchronization and broadcast signals are transmitted. The inter-cell coordinated scheduling is based on the static agreement on which antenna is active during the given subframe. This is illustrated in Fig. 1 where UE A and B are served by the center cell. At subframes when UE A is served, only the RAs are transmitting and the RF chains of the base station antennas are switched off. Similarly at subframes when UE B is served, only the base station antennas are transmitting



<sup>2</sup> OPERA-Net 2 (Optimising Power Efficiency in Mobile Radio Networks) project was partly funded by Tekes, the Finnish Funding Agency for Innovation. See [project home page](#) for further information.

**Fig. 1. Dominant interferers when the proposed method is used in the 3 sector deployment.**

and RF chains of RAs are switched off. This effectively reduces the number of dominant interferers and the power consumption.

Dynamic power control was not included to the LTE standard because the link adaptation can transfer the excess received power into increased spectral efficiency in most cases. However if the highest possible modulation and coding scheme (MCS) is already in use, the excess received power is lost and power consumption could be reduced by power control. The highest MCS is typically selected when the UE is close to the transmitting antenna – the situation that becomes more probable as the number of distributed antennas is increased. Although there is no fast mechanism for DL power control in LTE, the UE connection reconfiguration allows adaptation of the per-UE transmission power on a slower time scale. There is no exact way for the base station to know how much the per-UE transmission power can be reduced since there is no mechanism in LTE for UE to report its signal-to-interference-and-noise ratio values. As a workaround to this issue, we have proposed an algorithm in [6] that enables DL power control for low-speed users.

### Performance results

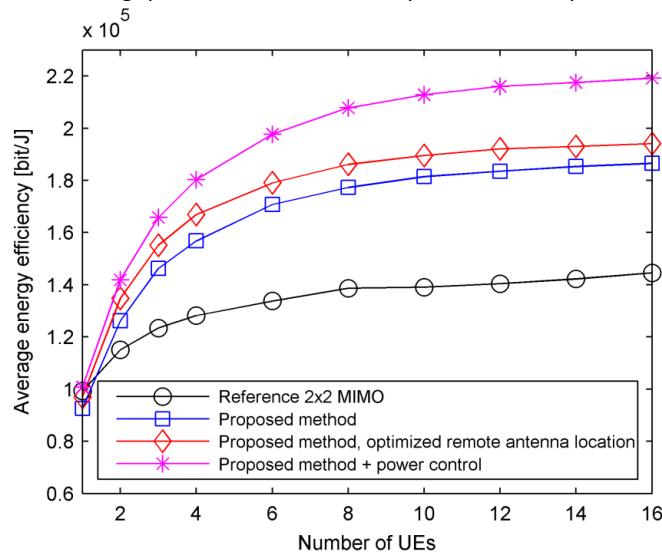
The performance of the proposed methods was evaluated by an accurate LTE DL link level simulator. The recommendations for simulating the performance of CoMP deployment scenario 4 given in [7] were mostly followed in the simulator. The used base station power consumption takes into account the power consumption in baseband processing, load-independent RF processing, and power amplifier. The power consumption parameter values were selected based on the inputs from partners in the OPERA-Net 2 project. The energy efficiency was defined as the ratio of cell throughput to the base station power consumption. The average energy efficiency of our proposed method is compared to the reference case of closed-loop spatial multiplexing with two antennas at the base station and two antennas at UE in Fig. 2. When there are 10 UEs per sector the energy efficiency gain from the proposed DPS and scheduling method is 30 %. The energy efficiency can further be increased by 6 % using the RA location that is optimized for cell edge spectral efficiency. Further optimization is possible by taking the DL per-UE power control into use. This brings further 17 % gain in energy efficiency making the total gain to 53 %. The amount of gain from the proposed methods is highly dependent on the power consumption modelling. This is further discussed in [5].

### Benefits

The main benefit of our methods is that they are fully compatible with the LTE-Advanced standard. Unlike most of the proposed improvements to LTE-Advanced energy efficiency, the methods are applicable also under heavy load. The basic idea of the DPS and scheduling method can be applied to any system based on distributed antennas, while the DL power control method can be applied to any LTE base station serving low-speed users.

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**Fig. 2. Energy efficiency as a function of the number of UEs in the 3-sector deployment with one RA per sector.**

#### 4.4 Energy efficient basestation transmission



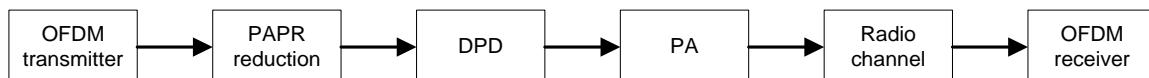
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##### Introduction

Energy efficiency is a very important topic in wireless communications. Especially in macrocells, the power amplifier (PA) has been by far the most power consuming element in a transmitter and thus it has been essential to increase its efficiency to save energy. However, when wireless communication is going to use smaller cells, the energy consumption of the PA is becoming comparable to the energy consumption of the other parts of the transmitter. In general, there is a trade-off between PA's nonlinearity, efficiency, and bit error performance. Hence, the methods used to improve the PA's efficiency and its energy consumption must be revisited in order to assess their true benefits in terms of energy saving.

The PA is the amplifier at the front end of the transmitter that amplifies the signal before it is sent to the channel. The PA can be characterised by its gain, nonlinearity characteristics and efficiency, which may vary according to the input signal properties, essentially its power and bandwidth. In practise, the PA is a nonlinear component, i.e. it distorts the transmitted signal. Digital predistortion (DPD) is a widely adopted method to compensate these distortions. The DPD compensates the distortions by using a nonlinear transfer function that can be thought as the inverse of the PA's transfer function. In addition, the energy efficiency of the PA can be increased by using the PA closer to its saturation point. This is enabled by decreasing the fluctuation of the transmitted signal envelope, i.e. using a method called peak-to-average power ratio (PAPR) reduction. This is particularly beneficial to communication using an orthogonal frequency division multiplexing (OFDM) type multicarrier techniques. In the OPERA-Net2 project<sup>3</sup>, the general goal was to investigate the trade-offs between the PA, DPD, and PAPR reduction in energy efficiency point of view. A simplified block diagram of the transceiver model used in this project is shown in Fig. 1.



**Fig. 1. System model used in the studies.**

##### PA modelling

To study the trade-offs, PA models need to be derived. The accuracy of the PA model is of high importance. One of the main reasons for PA modelling is the possibility to study means to counteract the nonlinear effect of the PA on the signal through digital predistortion, for example. Modern systems are very adaptive and versatile and their signal power and bandwidth may change to accommodate changes in the environment. Having a PA model that can be used for signals with varying power and bandwidth is crucial.

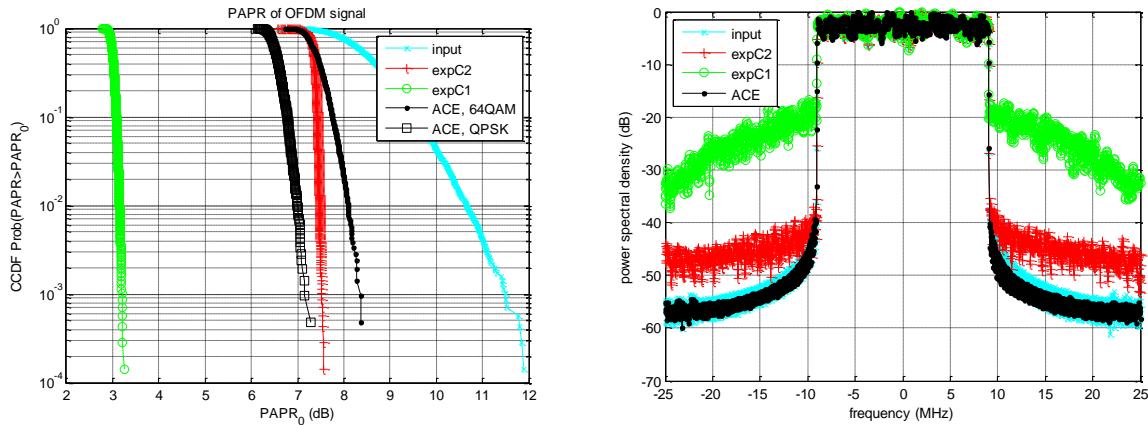
The PA modelling results from the measurements of a Doherty PA provided by Freescale Semiconductor are presented in [Boumard15]. The measurements have been done with various signal powers and bandwidths. The investigation focuses on whether a single model with fixed parameters could be used to model the PA's behaviour for signals with various bandwidths and powers. The accuracy of such a model is also assessed. Several PA models are used and compared to find an accurate modelling approach.

##### PAPR reduction

Several PAPR reduction methods are studied in [Hekkala14]. Different exponential companding (expC) methods are compared considering the performance trade-offs between PAPR reduction, bit error rate (BER), and

<sup>3</sup> OPERA-Net 2 project was partly funded by Tekes, the Finnish Funding Agency for Innovation. See [project home page](#) for further information on the project. Co-operation with Freescale and Thomson Broadcast is acknowledged here.

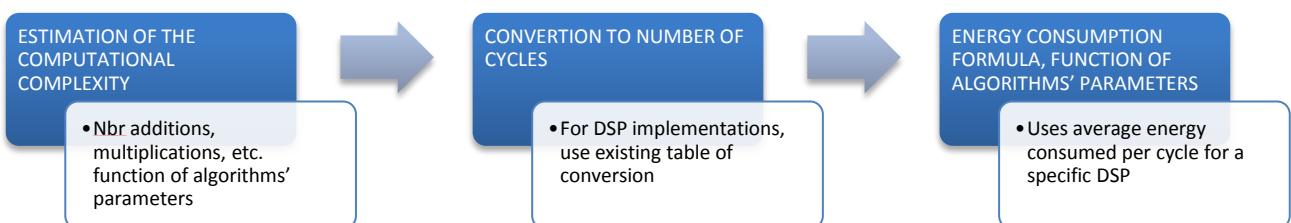
spectrum leakage. Moreover, another PAPR reduction method called active constellation extension (ACE) is studied. The ACE method has been defined in one of the European Telecommunications Standards Institute (ETSI) Digital Video Broadcasting (DVB) standard. To improve the PAPR reduction performance, modifications of the method are proposed. Fig. 2 shows an example of achievable PAPR reductions using the studied methods with various modulation formats. A common target PAPR for the LTE signal is about 7.5 dB. We can see from Fig. 2 that ACE with QPSK signal is better than that. In addition, ACE does not degrade spectrum that can be seen in the right-hand side of Fig. 2.



**Fig. 2. PAPR and spectra of OFDM signal using different PAPR reduction methods.**

### Energy consumption trade-offs

An insight on the trade-off between using the PA in its linear behaviour region and using it close to its saturation are given in [Boumard14]. When working in the linear region, the PA usually exhibits poor energy efficiency. Closer to the saturation region, the PA is more nonlinear and the help of the DPD and PAPR reduction is needed. The focus is what happens when the transmitted signal power is not very high, e.g. in femtocells. In these scenarios, the PA still consumes a lot of energy but the energy dissipated in the other components must also be accounted for. The energy consumption calculations used in the study estimates the energy consumption in the DPD, PAPR reduction as well as the PA. The calculations can be easily changed to other methods and integrated to other parts of the system. Fig. 3 shows the process used to estimate the energy consumption. The results show that the automatic use of a PAPR reduction method and a DPD must be revisited in terms of energy saving for the cases when the signal power is not large and the energy dissipated in the other components cannot be ignored.



**Fig. 3. Energy consumption estimation process.**

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## **5 Reliability for 5G and critical infrastructures**

**5.1 Interworking of communication and electricity networks**

**5.2 Physical layer security**

**5.3 Secure communication using orbital angular momentum based radio**



## 5.1 Interworking of communications and electricity networks



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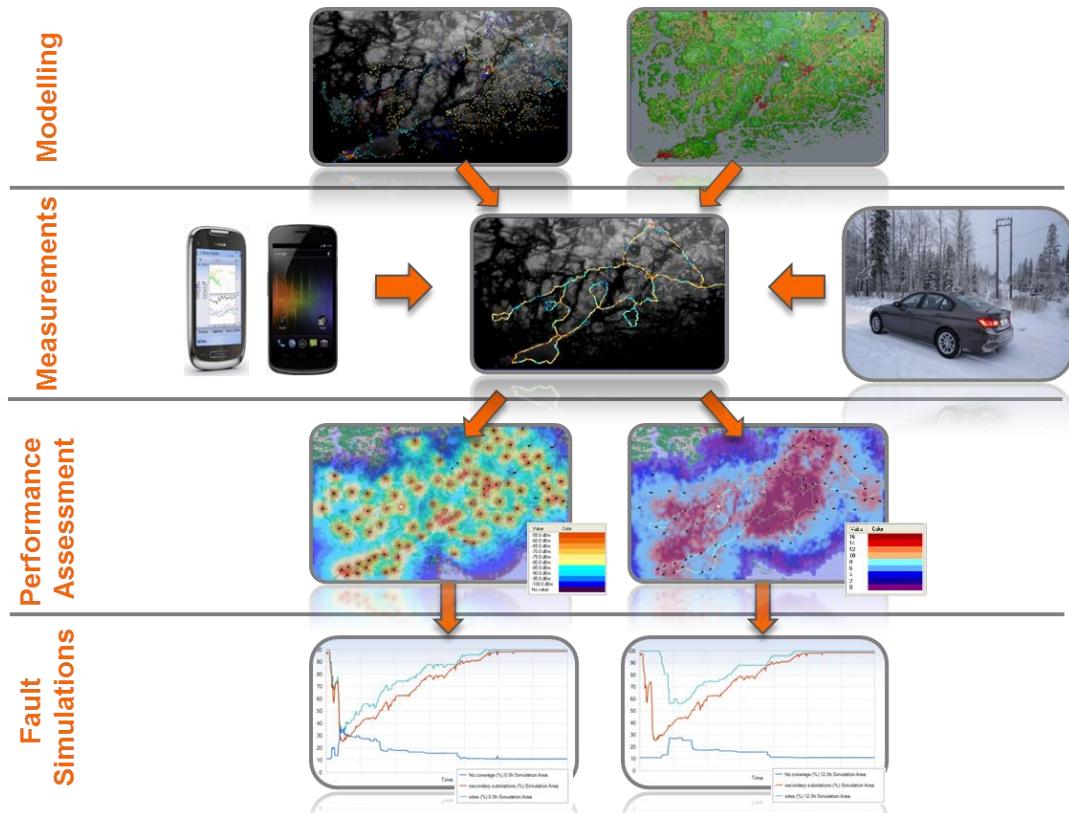
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### Need

Interdependency of mobile communication and electricity distribution networks has increased due to automation and digitalization. Loss of electricity and communication capabilities can cause chain-effects jeopardizing critical infrastructure services. For example, storm Patrick swept over the Scandinavian peninsula in 2011 and caused severe outages in southern parts of Finland and ~ 60 M€ damages to energy companies. The ongoing modernization of grids and anticipated climate changes have motivated energy companies to seek new cost-effective and reliable wireless technologies to enable real-time remote control and monitoring of electricity grids both in urban and rural areas. The goal of our work was to make future telecommunications and electricity distribution networks more adaptive and resilient, and to develop measurement and analysis tools to discover potential vulnerabilities in interworking communications and electricity networks.

### Approach

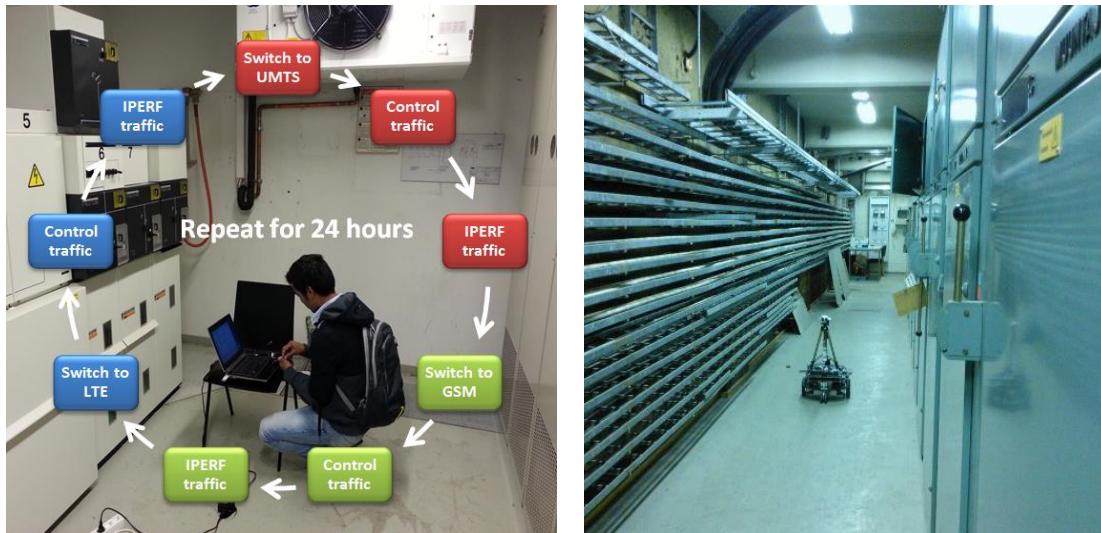
A measurement and analysis tool was developed to analyze interdependencies between electricity distribution and telecommunications networks in various fault scenarios. The tool shows the status of electricity distribution network and mobile networks both in normal and fault situations (Fig. 1).



**Fig. 1. Measurement and analysis tool for resilient and reliable communication.**

The developed measurement and analysis tool (Network Planning Tool, NPT) supports both rural and urban area fault analyses. It uses mobile network and electricity grid structure information with 3D terrain and building data to construct a situational picture of mobile networks' coverage and redundancy. The calculation models are fine-tuned and validated with field measurements performed in multi-operator 2G/3G/4G and

WLAN networks. The approach involves also the development of novel algorithms for grid and Machine Type Communication (MTC) to cope with power outages by utilizing advanced features introduced by LTE, targeted to critical communications and public safety applications. Low latency, high availability, and ultra-reliability are the driving forces of this work. A significant number of grid components are indoors, e.g. in basements. These environments are challenging and require more detailed information for the planning of wireless communications. Consequently, a mobile robot is used to support indoor measurements and coverage estimations.



**Fig. 2. Analysing grid communications capabilities in indoor environment.**

### Benefit

The tool and complementing measurements in 2G/3G/4G/WLAN networks help energy companies to decide where and when to exploit wireless communications for grid communication. The tool enables utility companies to test different technologies or structural solutions to improve resiliency and availability, and to shorten the recovery time. Moreover, the increased knowledge of interdependency of these networks makes it possible to discover potential point-of-failures in both networks and to react proactively.

### Competition

The electricity and communication network analysis is an essential aid to reduce the recovery time and to make grid communication more fault-tolerant, which in turn minimizes Operating Expense (OPEX) costs. The tool promotes automation and wireless remote control, which helps companies to build cost-effective remote control systems. Rescue services and municipalities can utilize the results in two ways: to discover the critical point-of-failures in existing critical infrastructures, or to use it in the planning of forthcoming infrastructures.

### Acknowledgements

The work was conducted in CLEEN-SHOK SGEM (Smart Grids and Energy Markets) and Tekes funded CONCARI (Communication and Control for Critical Infrastructures) projects.

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## 5.2 Physical layer security



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### Need

Wireless networks have become an inherent part of our daily life. We use our smartphones to browse the Internet, read our emails, stay in touch with our friends on social networks, use mobile banking, perform online credit card transactions, watch mobile TV, connect home entertainment appliances, etc. Wireless networks are also used in a way which is not directly visible to us, for example, utility companies may use remotely readable meters to measure our usage of electricity, heat, or water. Security of wireless communications becomes a critical issue when we so heavily rely on wireless networks to exchange sensitive and private information.

The information we share wirelessly is intended to reach specific recipients, and only them. Unfortunately, the wireless medium is broadcast medium because radio waves can propagate freely in all directions. The broadcast nature of wireless communications makes it difficult to prevent unauthorised access to transmitted information. Hostile adversaries can relatively easily intercept wireless transmission. Moreover, adversaries may launch various attacks on the wireless network. For example, adversaries may attempt to gain unauthorised access to information or resources, modify the conveyed messages, extract location information of a particular transmission node, or disrupt the information flow.

Securing wireless transmission is a challenging engineering task. In our research, we started our research from identification of possible threats and attacks on wireless networks. We illustrate them in Figure 1. The green boxes denote passive attacks where attackers do not attempt to disrupt information transmission but rather steal transmitted information. The two most common passive attacks are eavesdropping and information disclosure by traffic analysis. The blue boxes, on the other hand, denote active attacks where attackers usually try to alter the transmitted information and thus they significantly interfere with normal network operations. The most common active attacks include denial-of-service attacks, replay attacks, and message tampering attacks.

Most of security methods in use nowadays rely on cryptographic techniques employed at the upper layers of wireless networks. For cryptographic solutions to work, users and network access points must first share a common secret, for example, a cryptographic key. In general, these secret keys could be pre-shared or they can be exchanged by key exchange protocols. Cryptographic solutions have, however, a number of disadvantages. First of all, shared secret keys are difficult to establish at the early stages of the Radio Access Protocol. Furthermore, encryption and decryption processes introduce extra delays and require additional computing resources which reduce energy efficiency.

### Approach

Physical layer security<sup>4</sup> solutions are not based on cryptographic algorithms or secret keys, though they may support such solutions. Instead, physical layer security techniques take advantage of the physical characteristics of radio transmitters and radio channels, for example, transmitter nonlinearities, channel dispersion, and channel fading. In general, the physical layer security solutions can be classified into five categories: information-theoretic secrecy, channel, code, power, and signal design approaches. We illustrate various physical layer security solutions in Figure 2.

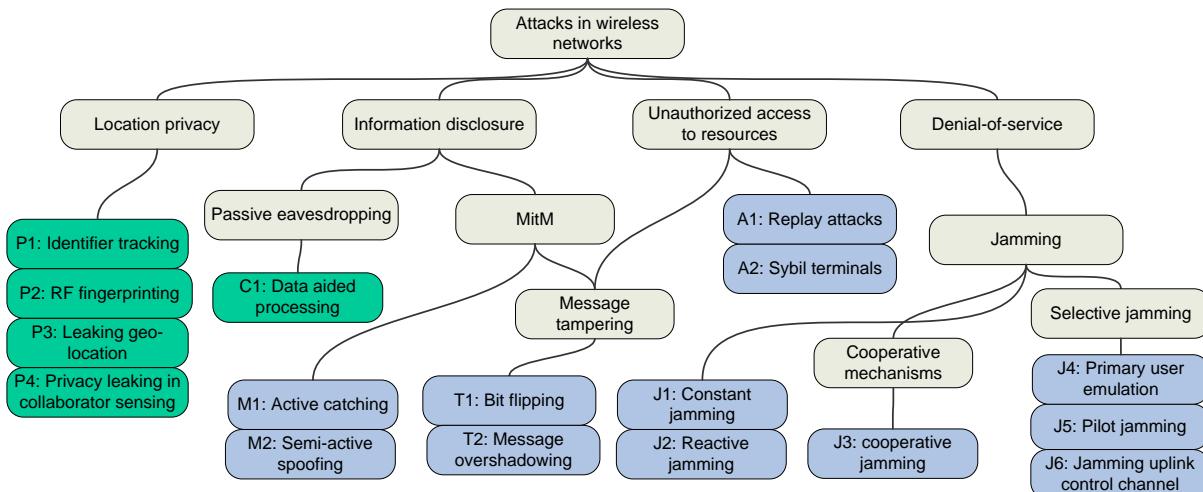
In information-theoretic approaches one attempts to arrange communication channels in such a manner that the signal-to-noise ratio (SNR) observed by legitimate user is much greater than the corresponding SNR observed by eavesdropper, which makes eavesdropping extremely difficult. Information theoretic security can be achieved by using special secrecy coding or intelligent jamming, either single-user or cooperative, where the artificial noise is generated such that it affects only potential eavesdroppers. In channel-based physical layer security, the local measurements of a radio channel are used to construct secret keys which can be then used as cryptographic keys in other communication layers. This process is typically referred to as the key

<sup>4</sup> This work was supported in part by EU FP7 project [PHYLAWS](#) (EU FP7-ICT 317562).

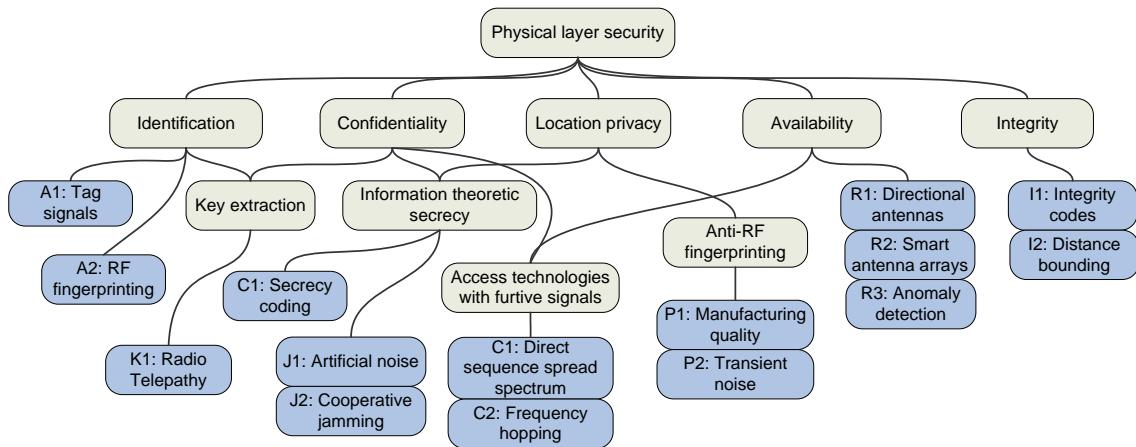
extraction. In code-based approaches, spread-spectrum modulation techniques are typically used to obscure information transmission. Power-based approaches, on the other hand, include various schemes with smart antennas and artificial noise injection schemes. In those schemes, the basic objective is to make the adversary's channel noisier than the desired user channel. Finally, signal design approaches include various schemes where an artificial noise is injected into transmitter signal to impair the adversary's ability to correctly estimate the channel.

### Benefits

Physical layer security solutions are complementary to already existing security solutions. In physical layer security solutions only the signals at the physical layer are processed and thus the security of wireless communication systems is enhanced in a simple and energy efficient way. Furthermore, since physical layer security solutions require very limited interaction with upper layers of the transmission protocol and with network management, physical layer security solutions are able to seamlessly address a wide class of wireless applications in the coming future. The main advantages of physical layer solutions are: limited impact on terminal and network architectures, ease and low cost of integration, full compatibility with existing encryption solutions and existing radio access technologies, and negligible impact on spectral efficiency.



**Fig. 1. Taxonomy of threats and attacks on wireless networks.**



**Fig. 2. Objectives of physical layer security and example solutions.**

### Related publications

F. Delaveau, A. Evesti, J. Suomalainen, R. Savola, N. Shapira "Active and passive eavesdropper threats within public and private civilian wireless networks - Existing and potential future countermeasures – An overview", in *Proceedings of the Wireless Innovation Forum Conference on Wireless Communications Technologies and Software Defined Radio*, June 11, 2013, Munich, Germany.

A. Evesti, J. Suomalainen, R. Savola, "Security risks in the short-range communication of ubiquitous application," in *Proceedings of the 8th International Conference for Internet Technology and Secured Transactions (ICITST)*, December 9-10, 2013, London, United Kingdom.

J. Suomalainen, A. Evesti, and A. Kotelba, "Security pairings using physical layer properties of wireless communications," in *Proceedings of the 2nd International Conference on Privacy and Security in Mobile Systems (PRISMS)*, May 11-14, 2014, Aalborg, Denmark.

## 5.3 Secure communication using orbital angular momentum based radio



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### Need

The broadcast nature of the wireless communication medium makes it hard to eliminate unauthorized access to wireless networks. For that reason, it is relatively easy to eavesdrop or alter radio signals. In conventional communication systems, the protection of own information is usually achieved by obscuring the information transmission using cryptography, special modulation schemes such as spread-spectrum modulation, or both. However, security of wireless communication systems can be enhanced by using physical layer security extensions. One of such possible physical layer security extensions is the radio transmission using so-called orbital angular momentum (OAM) wave modes.

### Approach

Electromagnetic field possesses energy and linear momentum. The fact that electromagnetic field also possesses angular momentum is probably not adequately stressed in textbooks despite the fact that such electromagnetic fields were studied theoretically already by Poynting in 1909. The angular momentum of the electromagnetic field can be decomposed into spin angular momentum (SAM) and orbital angular momentum (OAM) as demonstrated by Humblet in 1943. Just as the electromagnetic field can exchange its energy and linear momentum with charged particles, it can also exchange its angular momentum with a system of charged particles often leading to rather surprising results. When a radio beam carrying a nonzero angular momentum impinges on a charged particle, its angular momentum can be transferred to the particle, thus setting it in rotational motion. If the particle is not at the beam centre the two angular momenta will give rise to different kinds of rotation of the particle. SAM will give rise to a rotation of the particle around its own centre, that is, to a particle spinning. OAM, instead, will generate a revolution of the particle around the beam axis.

The classical manifestation of SAM is circular polarization of a radio wave. The classical manifestation of OAM is, however, a more quirky thing. Let us just say that each OAM wave mode generates a unique spatial distribution of the electromagnetic field and spatial distributions corresponding to different modes are orthogonal to each other. Under some specific conditions, these spatial distributions can be detected by specially designed parabolic or circular antenna arrays. Example radiation modes of the first six OAM wave modes are shown in Figure 1. Spatial dependence of the phase of the electromagnetic field is shown using different colours for different values of the phase.

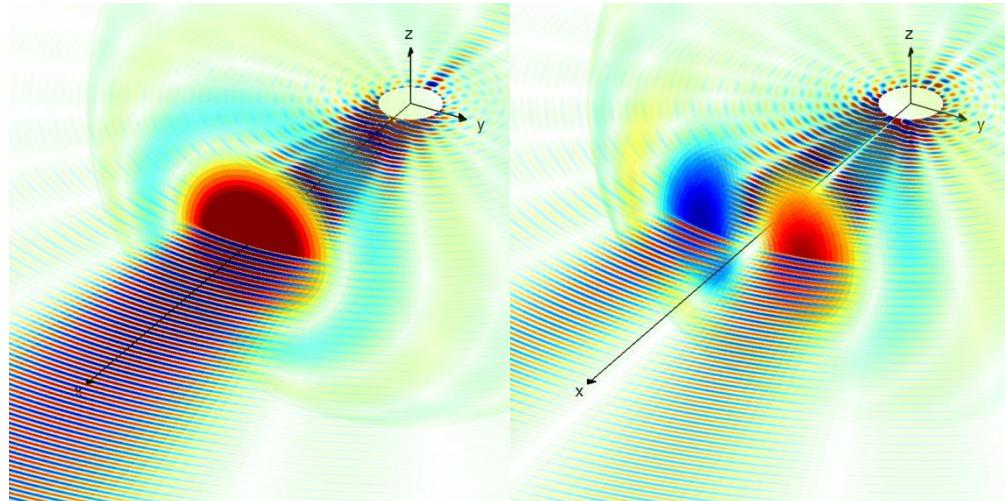
Transmissions techniques using orbital angular momentum wave modes of light were first studied in detail in 1990s and are rather well established, both in free-space and fibre optical communications. The first experiments with radio links using OAM wave modes have been done in 2011. So far, operation of radio links using OAM wave modes has been reported at the frequencies of 2.4 GHz, 10 GHz, 17 GHz, 29 GHz, 60 GHz, and 100 GHz over distances up to 440 m.

The possibility of creating highly secure communications links impervious to threats and external attacks by exploiting light OAM has already been recognized by Defense Advanced Research Projects Agency (DARPA). In 2011, DARPA funded research efforts related to secure communication using optical vortices. The researchers were to investigate the properties of light beams carrying OAM in optical fibers and their applicability to creating next generation secure encryption links, by encoding information in different OAM states.

### Research results

In our research, we studied the possibility to securely transmit information in wireless military systems using OAM based radio links. In particular, we theoretically studied the properties of OAM radio beams, methods to generate and receive OAM radio beams, and possible limitations of OAM based radios. We found that OAM wave modes can be nicely explained using theory of spherical wave functions. According to the theory of spherical wave functions, the electromagnetic field radiated by a transmitter can be completely described by

an expansion in a finite number of radiating spherical wave functions. At the receiver end, the same field can be completely described by an expansion in a finite number of local spherical wave functions. The coefficients of the two expansions can be linked through a translation matrix. Different OAM wave modes are generated by respective eigenvectors of a translation matrix. Furthermore, OAM wave modes form a set of additional independent parallel radio channels that can be exploited as additional degrees of freedom by the system designer. For example, they can be used to obscure information transmission by means of mode hopping. Nevertheless, there are certain limitations in using OAM wave modes.



**Fig. 1. Example OAM radiation modes: modes 1–2 in the left plot, modes 3–6 in the right plot.**

### Challenges

Perhaps one of the most important limitations is relatively fast decay of signal strength with the distance. In particular, while the two basic radio channels using two orthogonal polarizations decay as  $1/d^2$ , the additional radio channels using the OAM modes decay as  $1/(d^{2+2|m|})$  where  $d$  is the link distance and  $m$  is the order of the OAM mode. This is a direct consequence of the fact that for higher-order OAM wave modes, most of the transmitted energy is concentrated in a ring whose diameter increases with the distance. However, the weakness of the additional radio channels using the OAM modes can be compensated by enlarging the transmitter and/or the receiver antennas which sometimes is not practical.

From signal processing point of view, transmission of OAM modes shares many similarities to multicarrier transmissions. In particular, the orthogonality of OAM wave modes appears to be sensitive to a misalignment of the transmitter and/or the receiver and multipath propagation that can be understood as forms of spatial phase noise. For OAM wave modes, multipath propagation is a more subtle phenomenon because each reflection introduces OAM wave-mode swap from left- to right-handed one and vice versa. To cope with the problem of wave-mode swap, the receiver must be able to discriminate and, possibly, combine left- and right-handed modes, for example, by using a circular array of  $2M+1$  antennas.

### Security benefits

The sensitivity of the channel orthogonality to misalignments of the transmitter and/or the receiver and multipath propagation can be exploited to set up point-to-point secure radio links, for example tactical data links for Command, Control, Communications, Computers, and Intelligence (C4I) applications, which would be difficult to intercept and resilient to jamming.

### Acknowledgement

This work was partially funded by Scientific Advisory Board for Defence (MATINE).

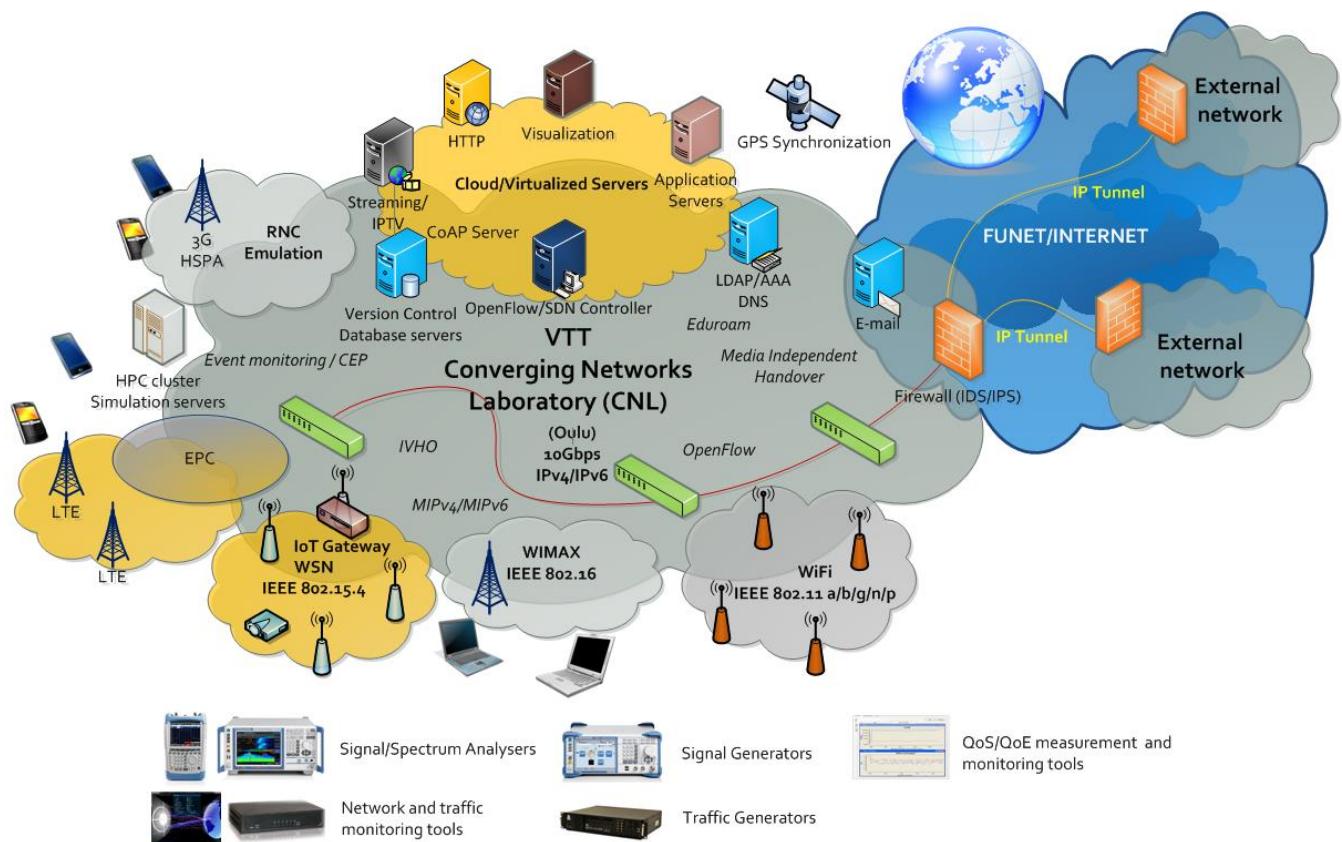
## **6 Network technologies and environments**

### **6.1 Control evolution for 5G mobile networks**

### **6.2 5G test network**

### **6.3 Monitoring and testing solutions for dynamic heterogeneous network environments**

### **6.4 Wireless mesh networking in challenging environments – Enabling Internet for industry and rural areas**



VTT's Converging Networks Laboratory.

## 6.1 Control evolution for 5G mobile networks



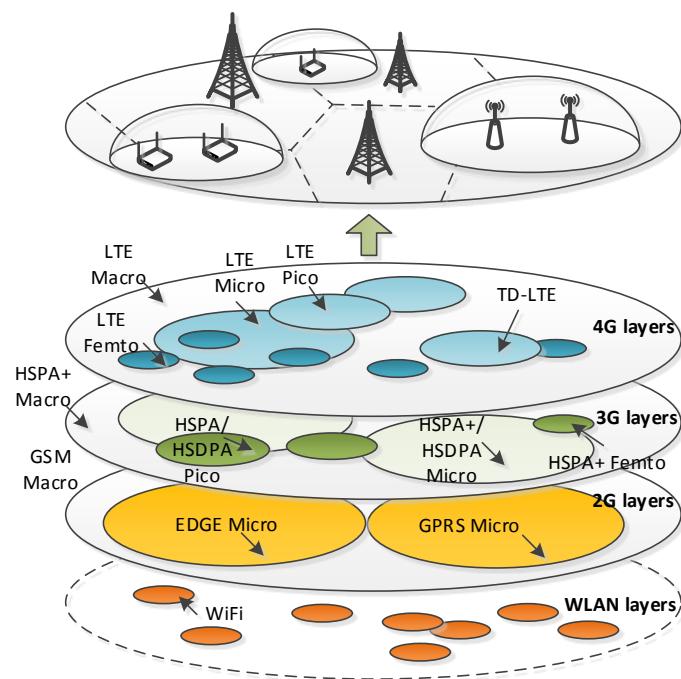
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Mobile networks tend to be extremely complex, leading to a big challenge in the efficient control and coordination of networks. The number of wireless devices is predicted to reach 7 trillion for 7 billion people by 2020. With more devices and emerging data-intensive services, mobile data traffic is estimated to be increased by 1000-fold in 2010-2020. To keep pace with such an enormous demand, the current available spectrum, spectrum efficiency and cell density of mobile networks have to be extended by at least a factor of 10. Naturally cells will be smaller for more capacity and denser for sufficient coverage. Next generation 5G mobile networks will be heterogeneous, densified, and highly flexible on spectrum use, as shown in Fig. 1.

Obviously, 5G mobile networks will not be built upon a single RAN technology as its predecessor, but through the harmonious integration of diverse network technologies to versatile low cost ubiquitous radio access networks.

Harmony will be inside the gene of 5G networks, in order to make seamless services delivery and meet the 5G key requirements. The development history of computer systems would give us a good reference model for the evolution of next generation communication networks. The hardware and functions of computer systems have become increasingly diverse and sophisticated while their full control for complex tasks remains simple through programs coded in high-level highly abstracted languages. The openness, flexibility and scalability come from the proper abstraction of low-layer functions in a hierarchical manner. We need similar abstraction and control approaches in 5G radio access networks so that we can orchestrate heterogeneous mobile networks to a ubiquitous and unified service platform.

The proper abstraction hides details of the low-layer implementation while providing only the necessary data for information exchange and high layer control and coordination. This will bring multiple key advantages to 5G networks: a) it will manage the complexity and greatly simplify the signalling for implementing advanced physical layer technologies; b) it will fundamentally extend self-organising network features in 5G as the abstraction enables low-layer control entities to speak the same “language”; c) it will offer network-wide programmable control for interference management, mobility and rapid deployment of new services, for which the abstraction is the essential step for high-level programmability; d) last but not the least, the network abstraction will provide operators a simple yet realistic overview on spectrum usage of their networks and thus pave a way for more efficient, accurate and advanced spectrum management in 5G networks.

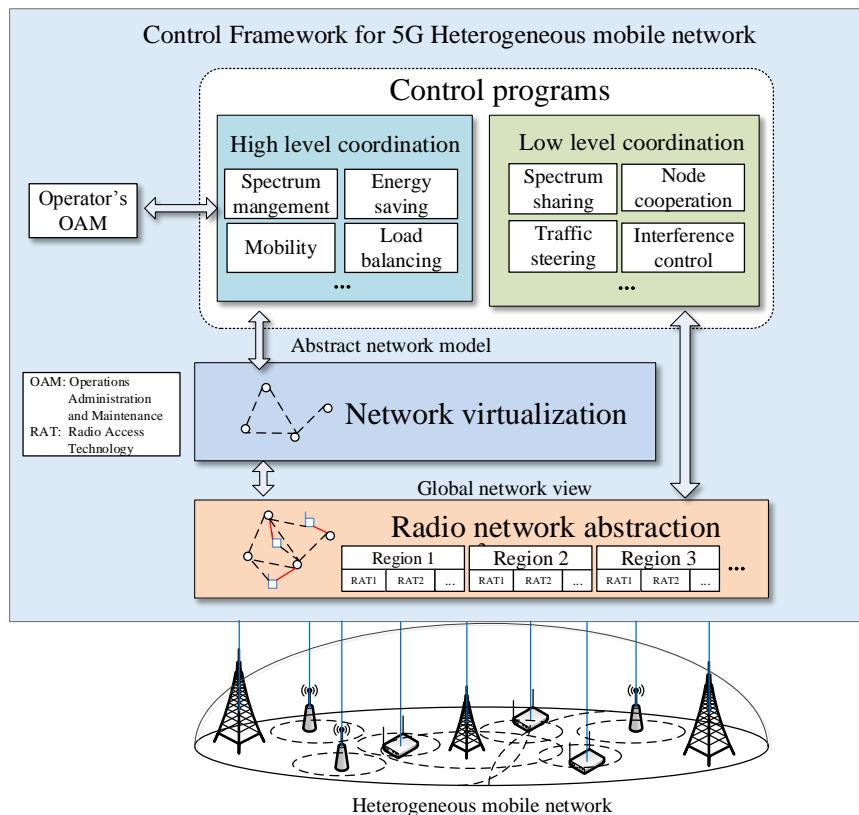


**Fig. 1. Heterogeneous mobile networks.**

Abbreviations: EDGE: Enhanced Data-rates for Global Evolution, GPRS: General Packet Radio Service, GSM: Global System for Mobile Communications, HSDPA: High-Speed Downlink Packet Access, HSPA+: Evolved High Speed Packet Access LTE: Long Term Evolution, TD-LTE: Time Division LTE, WiFi: Wireless Fidelity, WLAN: Wireless Local Area Network.

Therefore we propose the control framework for 5G heterogeneous mobile networks, as shown in Fig. 2, with the following key features:

- **Physical and MAC layer abstraction**, to provide a simple network view of low-layer reality, and thus to enable a scalable and flexible control and coordination framework for complex resource coordination and spectrum management in 5G networks;
- **Programmable control based on the low-layer abstraction** with well-defined open control interfaces and protocols to greatly simplify the management of heterogeneous mobile networks;
- **Flexible and coordinated spectrum management** based on full awareness of spectrum usage through the network abstractions, to support fine-granularity spectrum management for licensed share access (LSA), inter-operator spectrum sharing in radio access networks.



**Fig. 2. Proposed control framework for 5G heterogeneous mobile networks.**

In summary, our vision on control and coordination in 5G heterogeneous mobile networks is a simple, open, unified and programmable control framework powered by proper abstraction of low-layer states, behaviours and functions, common control protocols, interfaces and primitives for network coordination and automation, and hierarchy abstraction on network states for efficient resource allocation and spectrum management in the network. For more detailed information of proposed control framework, please refer to our related publications listed below in this article.

#### Related publications

T. Chen, H. Zhang, X. Chen, and O. Tirkkonen, "SoftMobile: Control Evolution for Next Generation Heterogeneous Mobile Networks" *IEEE Wireless Communications Magazine*, December 2014.

X. Zhou, Z. Zhao, R. Li, Y. Zhou, T. Chen, Z. Niu, and H. Zhang, "Towards 5G: When Explosive Bursts Meet Soft Cloud," *IEEE Network Magazine*, November 2014.

## 6.2 5G test network (5GTN)



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5G Test Network (5GTN) is a two years research project, where VTT Technical Research Centre of Finland Ltd and University of Oulu, together with their industrial partners, are building a 5G test network at Oulu, Finland. In the test network, critical new 5G technologies can be developed and it will allow testing of the performance of the new technologies in a realistic environment.

The 5GTN environment will be linked to theoretical 5G research and will provide the opportunity to validate theoretical results. It will constantly evolve, as research and standardisation progress. Hence, technologies will be comprehensively verified before they are standardised and implemented. By 2020, the environment will have evolved into a full-scale 5G network, which will be provided as a living lab for application and service testing. The test network will strengthen Finland's position at the cutting edge of international 5G development.

### Short introduction of 5G

5G will be the next big step in wireless communications – it will offer multimedia and cloud services of very high quality, enable the future internet of things (IoT), and reduce material and energy consumption. 5G will form the infrastructure of the traditionally fast-growing wireless multimedia communications, as well as for massive communication between devices. While requiring significant architectural changes and the application of new technologies, 5G must also provide a seamless transition from the current system architecture and technology to the new one.

The network structure for 5G supports the use of several transmission technologies and the direct integration of different services with the network. It also supports the needs of the internet of things and the industrial internet. Overall, the new technology will enable very high quality multimedia and cloud applications, as well as allowing the deployment of extremely high density networks.

### 5GTN overview

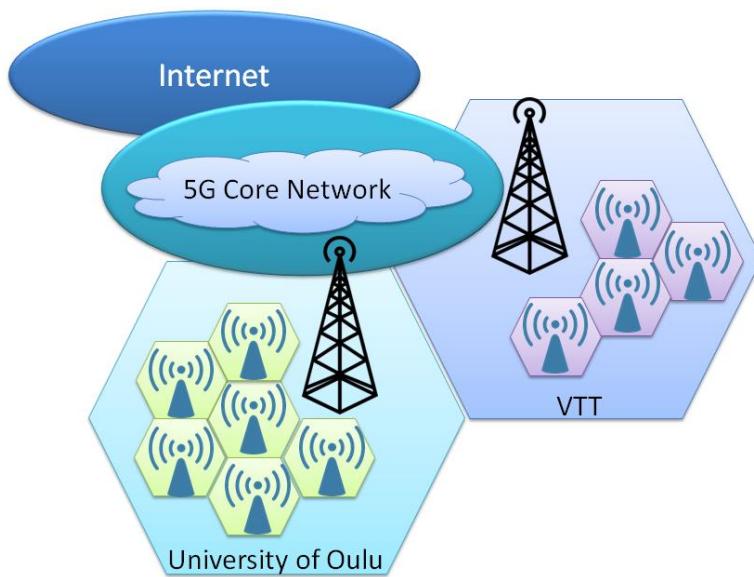
In the beginning, the test network is divided into two sites: one in the VTT's premises and another at the University of Oulu. A core network connects these two sites together. The test network can also be connected to other networks via internet. Both of the network sites include a macro cell and small cells inside the coverage area of the macro cell. At least in the beginning, management and operation of the test network is handled by VTT. Fig. 1 below presents the preliminary architecture for the first phase of the 5G test network to be developed as a part of the project.

There are three focus areas in the project, namely Air interface, Network management, and Testing technology. In the Air interface focus area, the idea is to update LTE radio access technology features to accommodate expected 5G architectures and capabilities. In the beginning, the research will be focused to support e.g. reliability, very low latencies, high scalability of data rates, and superb energy efficiency. In the Network management focus area, the intention is to design a modular networks management tools for collection, processing, and distribution of information. A real time (or at least close to real time) network element monitoring is one of the main goal in the project. The test network is part of VTT's converging network laboratory, which gives additional advantageous to do extended studies e.g. feasibility of SDN (software defined networking) and NFV (network functions virtualisation) concepts in multi-RAT (radio access technology) environments. Testing technology focus area provides information about physical and network level events in

the test network. Different test types and system testing tools for new solutions will be studied. In addition, cognitive testing capabilities will be considered.

The test network supports R&D and testing in a realistic 5G network environment. It will be a dynamic and heterogeneous platform for developing and testing new applications, services, algorithms, technologies, and systems. It increases competence to the Oulu area in 5G development and standardisation domain and gives to the national industry a forerunner position in 5G technologies globally. Synergy benefits will be achieved by the long term cooperation between the players of the whole wireless communications ecosystem. The test network supports business development assessments e.g. for new operator business models as well as offering parts of the network as open test environments for third parties. Finally, during the project time, the test network will be upgraded for the full-scale 5G network using 5G devices, higher frequency bands, cognitive management functionalities, and system testing tools for new solutions.

In the VTT's site of the network, i.e. in the restricted network, companies can test the functionality of their technologies, while in the University of Oulu's site, i.e. in the public network, solutions such as those for the large-scale deployment of user devices can be verified. The intention is to offer the public part of the network, based on rules yet to be defined, as an open test environment for all willing partners. In addition, the test network will be expanded to cover different parts of the city on a more open basis. In this way, the test network can be used as a platform for developing and testing new applications.



**Fig. 1. General architecture of the test network.**

### Acknowledgments

The project is part of Tekes 5thGear –program ([tekes.fi/5g](http://tekes.fi/5g)) and funded by Tekes, VTT, University of Oulu, and participating industrial partners. The industrial partners are as follows: Anite Finland, Elektrobit Wireless Communications, Eltel Networks, EXFO, Haltian, Indalgo, MediaTek, Nokia Solutions and Networks, Pehutec, Pulse Finland, Sarokal Test Systems, and Yleisradio. City of Oulu, Finnish Communications Regulatory Authority, and Oulu University of Applied Sciences are as supporting partners.

### More information

More information can be found from the project web page: [www.5gtn.fi](http://www.5gtn.fi).

### 6.3 Monitoring and testing solutions for dynamic heterogeneous network environments



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The increasing heterogeneity and densification of wireless networks together with autonomous network management schemes and dynamically changing system configurations are causing challenges for efficient monitoring and testing of future communication infrastructures. As the flexibility of the target systems increase, the traditional monitoring and testing solutions designed for fixed system configurations must be re-designed. However, even though the new capabilities of wireless networks require new capabilities from the monitoring and testing solutions, they also offer new possibilities when it comes to cost efficient implementation of highly granular monitoring fabrics and interactive testing approaches for heterogeneous networks.

#### Testing challenges in dynamic heterogeneous networks

The continuing trend of increasing network heterogeneity introduces numerous new challenges into the network monitoring and testing domains. Taking into account the key features of future heterogeneous network infrastructures, including both small cell enhancement and composite network scenarios, the monitoring and testing framework must be able to adapt at least to the following system characteristics:

- Complex and dense multi-layer network architectures
- Dynamically changing role of small cells and rapid uncoordinated deployment of new cell sites
- Large load variations between neighbouring cells and varying capabilities of cell site backhaul links
- Cooperative control mechanisms and self-organising networks
- Varying spectrum use scenarios and cognitive radio systems
- Energy profiling of heterogeneous network nodes
- Varying interfaces and protocols

In this operational environment, an efficient monitoring and testing framework must be able to minimise the control signalling overhead, re-configure itself according to the changes in the target system, support multipoint measurement capabilities, provide means for end-to-end performance assessment and configuration verifications, collect both device and network level information related to consumption of basic communication resources, and be able to monitor and analyse multiple control and user plane protocols from interfaces located at different network layers. If all these functionalities are implemented relying on traditional monitoring and testing solutions, where dedicated hardware is extensively utilised to create a parallel out-of-band infrastructure for the related control signalling, the cost of monitoring and testing heterogeneous networks deployed in large geographical areas quickly increases to an unfeasible level. Hence, other more cost effective solutions should be used to realise the desired functionality for the heterogeneous network's monitoring and testing framework.

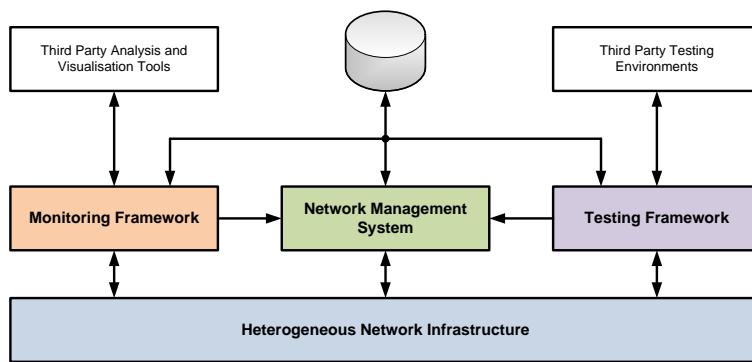
#### Testing solutions for dynamic heterogeneous networks

The overview of the monitoring and testing concept developed in Cognitive and Intelligent Solutions for Testing and Monitoring of Future Access Technologies (COIN) project<sup>5</sup> is shown in Fig. 1. The concept is built around three main components that are interconnected with the management system of the heterogeneous network:

1. Highly adjustable monitoring framework based on programmable network elements
2. Interactive testing framework based on virtualisation techniques
3. Network state database for centralised distribution of real time and history data related to the system

<sup>5</sup> This work has been supported by the Cognitive and Intelligent Solutions for Testing and Monitoring of Future Access Technologies (COIN) project, which is a collaborative effort between four industrial partners (Anite, EXFO, Nokia, and Rugged Tooling), and two research organizations (University of Oulu Centre for Wireless Communications and VTT Technical Research Centre of Finland). The work was partially funded by Tekes.

The monitoring framework adapts to the prevailing network conditions. During normal operation, fewer monitoring points can be used and aggregated high level performance metrics utilised. This way, the required amount of control signalling related to monitoring activities during normal operation can be minimised. In case of performance problems, more detailed performance metrics can be gathered from the network elements and more monitoring points can be activated to different parts of the network infrastructure for troubleshooting purposes. When the source of the problem is located, all necessary traffic from the faulty network segment can be directed for detailed analysis e.g. to a resource pool consisting of third party analysis and visualisation tools. The monitoring fabric utilised in heterogeneous network infrastructures should be based on the capabilities of the monitored network infrastructure and it should not require additional dedicated monitoring hardware in order to work. Hence, utilisation of Software Defined Networking (SDN) and Network Functions Virtualisation (NFV) principles in the heterogeneous network infrastructure are important prerequisites for the implementation of the COIN monitoring framework.



**Fig. 1. COIN monitoring and testing concept.**

The testing framework can be utilised by the network management system to validate the performance of new configurations before they are taken into use in the production network. It can also be used to troubleshoot the network with the help of predefined test cases in case of deteriorated network performance. The testing environment is implemented inside the production network as a separate virtual network segment. With this online approach, the testing environment, utilising the same physical resources as its target network, can achieve more accurate testing results and offer them as an additional input to the decision making process of the network management system. In addition to the online testing approach, the testing framework can be connected to third party offline testing environments, which can offer additional testing functionalities based e.g. on simulations or statistical models.

The network state database is a centralised depository of both real time and history data of the heterogeneous network's performance and configurations. As all data related to the operation of the network services and the underlying infrastructure is available from a single source, the database facilitates utilisation of further automation and machine learning techniques in the monitoring and testing frameworks as well as in the heterogeneous network management system. In addition, it offers a straight forward access to the information also to other systems related e.g. to cyber security or network service development.

### Enabling technologies

The presented COIN monitoring and testing concept relies heavily on technologies such as Self-Organising Networks (SON), NFV and SDN which are currently seen as the key building blocks of future network infrastructures. Hence, even though the functionalities required to implement the concept do not yet exist in large scale commercial networks, they will inevitably become a central part of the constantly evolving mobile networks in the coming years.

### Related publications

J. Pinola, J. Perälä, P. Jurmu, M. Katz, S. Salonen, J. Piisilä, J. Sankala, and P. Tuuttila, "A Systematic and Flexible Approach for Testing Future Mobile Networks by Exploiting a Wrap-around Testing Methodology," in *IEEE Communications Magazine*, vol. 51, no. 3, March 2013.

J. Pinola, A. Anttonen, and M. Katz, "Monitoring and Testing Challenges in Heterogeneous Wireless Networks," submitted to the Springer Journal on Telecommunication Systems.

## 6.4 Wireless mesh networking in challenging environments – Enabling Internet for industry and rural areas



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Humans as the data producers and consumers are dominating today. However, the amount of machines that are producing data and communicating with each other is growing rapidly. Having billions of networked devices is creating challenges to the way how communication infrastructure is utilised. The ubiquitous network connectivity becomes a critical requirement for many of the applications. And while the digitalisation of the society and industry is continuing, we cannot omit the fact that around the globe geographically vast areas and large number of people are still lacking proper Internet connectivity.

It is clear that the future industrial Internet and ubiquitous Internet connectivity is based on heterogeneous technologies where different type of wireless mesh networks have an important role.

### Wireless communication needs in challenging environments

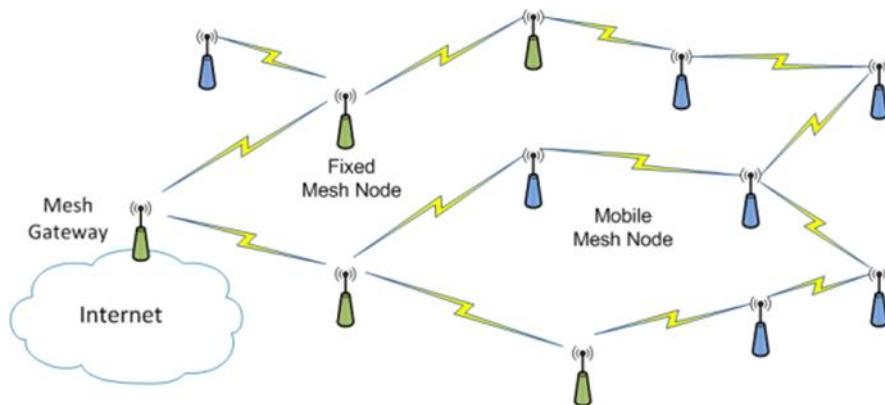
Nowadays, more and more devices are moving freely in rather dynamic manner, requiring wireless communication. Different applications clearly have varying requirements pertaining wireless communication. Industrial applications, e.g. motion sensing and control, as well as alerting, often have time-critical communication demands where data delivery and latency must be guaranteed. On the other hand, massive amounts of bulk data, e.g. log information, might be gathered from numerous sources and transmitted concurrently over wireless networks for storage and analysis. Moreover, the harsh industrial environment with large amounts of metal and concrete structures poses challenge to radio signal propagation and coverage. Guaranteeing the connectivity requires dense access point installation or use of mesh networking.

Another challenging application area is networking in rural areas and in emerging regions. The distances are great and power is a scarce resource. Due to the lack of existing infrastructure, wireless communication seems the only viable way of building communication networks. Here, power-efficiency, low-cost hardware, and low maintenance need and operational costs are the key drivers. Use of mesh networking helps enhancing robustness against occasional node and link failures and also offers rather simple extension of the network connectivity coverage.

### Mesh networking

Wireless mesh networks can be constructed in many ways but common to all are that nodes have the ability to communicate not only with their direct neighbours but with all the nodes that belong to the same mesh configuration. Each node in the specific mesh is relaying packets to and from their neighbouring nodes. Different algorithms and metrics can be chosen for the packet forwarding and path selection processes that are usually chosen uniform within one mesh network. Communication with external networks or nodes requires gateway functionality in one or more of the mesh nodes that forward traffic between the external network(s) and the mesh.

Dynamic routing and multiple paths between the nodes increase the robustness and help maintain connectivity when individual nodes are moving or lose connectivity (Figure 1).



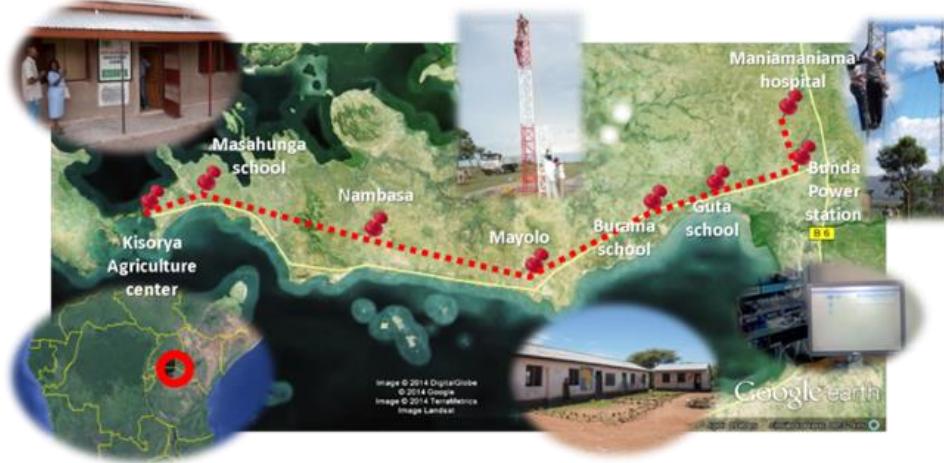
**Fig. 1. Mesh network consisting of fixed and mobile nodes.**

### Benefits of WiFi mesh networks

Wireless mesh networks that are based on WiFi technology can fulfil the demands of many application areas. Whereas traditional sensor mesh networks are often optimised for low-energy and offer fairly low bandwidth, WiFi mesh supports relatively high bandwidth and better coverage. The availability of inexpensive standardised WiFi hardware and use of license-free spectrum are the advantages of WiFi technology. However, the use of shared spectrum and lack of certain capabilities might hinder its use as the only communication channel in critical applications that require absolute reliability or strict guaranteed QoS.

### Results

The Celtic-Plus CIER project has demonstrated the feasibility of low-cost WiFi technology and mesh networking for connecting people in rural areas (Figure 2). The goal was to connect an Internet gateway located in Bunda, Northern Tanzania, to an agriculture centre in remote Kisorya, around 90 kilometres apart from each other. Along the route, the intermediate mesh nodes also provide network access to nearby villages and schools. The equipments were installed there permanently to support the local government's mission on promoting ICT services for local people.



**Fig. 2. WiFi based wireless network deployment in Bunda, Tanzania that was carried out in Celtic-Plus CIER project.**

### Acknowledgements

The research work was carried out in EU Eureka Celtic-Plus CIER project and partly in AWARENESS project as part of VTT's Critical technologies towards 5G program.

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## **7 Publications**

### **7.1 Scientific journal and magazine articles (2013)**

#### **Secondary terrestrial use of broadcasting satellite services below 3 GHz**

Marko Höyhtyä

International Journal of Wireless & Mobile Networks (IJWMN) Vol. 5, No. 1, February 2013.

DOI : 10.5121/ijwmn.2013.5101

#### **A systematic and flexible approach for testing future mobile networks by exploiting a wrap-around testing methodology**

Jarno Pinola, Juho Perälä, Petri Jurmu, Marcos Katz, Seppo Salonen, Jonne Piisilä, Jouko Sankala, and Pekka Tuuttila

IEEE Communications Magazine, Vol. 51, No. 3, March 2013.

DOI: 10.1109/MCOM.2013.6476882

#### **Reducing pattern noise in blind energy detection of Nonnegative PAM symbols**

Antti Anttonen, Adrian Kotelba, and Aarne Mämmelä.

IEEE Communications Letters, Vol. 17, No. 4, Apr. 2013.

DOI: 10.1109/LCOMM.2013.021913.122715

#### **Simple rules for mobile network operators' strategic choices in future cognitive spectrum sharing networks**

Petri Ahokangas, Marja Matinmikko, Seppo Yrjölä, Hanna Okkonen, and Thomas Casey

IEEE Wireless Communications, Vol. 2, No. 2, April 2013.

DOI: 10.1109/MWC.2013.6507390

#### **Cognitive radio trial environment: First live authorized shared access-based spectrum-sharing demonstration**

Marja Matinmikko, Marko Palola, Harri Saarnisaari, Marjo Heikkilä, Jarmo Prokkola, Tero Kippola, Tuomo Hänninen, Markku Jokinen, and Seppo Yrjölä,

IEEE Vehicular Technology Magazine, Vol. 8, Issue 3, Sept. 2013.

DOI: 10.1109/MVT.2013.2269033

#### **Regressive admission control enabled by real-time QoS measurements**

Mirjami Jutila, Jarmo Prokkola and Despina Triantafyllidou

International Journal of Computer Networks & Communications. Vol. 5, No: 6, Nov. 2013.

DOI: 10.5121/ijcnc.2013.5602

#### **Energy efficiency of power-adaptive spatial diversity methods**

Olli Apilo, Mika Lasanen, Sandrine Boumard, and Aarne Mämmelä

IEEE Transactions on Wireless Communications, Vol. 12, No. 9, Sept. 2013.

DOI: 10.1109/TWC.2013.072313.120263

#### **Fuzzy-Logic Based Framework for Spectrum Availability Assessment in Cognitive Radio Systems**

Marja Matinmikko, Javier Del Ser, Tapio Rauma, and Miia Mustonen

IEEE Journal on Selected Areas in Communications, Vol. 31, No. 11, Nov. 2013.

DOI: 10.1109/JSAC.2013.131117

#### **Stochastic Power Adaptation with Multiagent Reinforcement Learning for Cognitive Wireless Mesh Networks**

Xianfu Chen, Zhifeng Zhao, and Honggang Zhang

IEEE Transactions on Mobile Computing, Vol. 12, No. 11, Nov. 2013.

DOI: 10.1109/TMC.2012.178

#### **Energy-Efficient Optimization for Wireless Information and Power Transfer in Large-Scale MIMO Systems Employing Energy Beamforming**

Xiaoming Chen, Xiumin Wang, and Xianfu Chen

IEEE Wireless Communications Letters, Vol. 2, No. 6, Dec. 2013.

DOI: 10.1109/WCL.2013.092813.130514

## 7.2 Scientific journal and magazine articles (2014)

### A 3-D Miniaturized High Selectivity Bandpass Filter in LTCC Technology

E. Arabi, M. Lahti, T. Vähä-Heikkilä and A. Shamim

IEEE Microwave and Wireless Components Letters, Vol. 24, No. 1, Jan 2014.

DOI: 10.1109/LMWC.2013.2285285

### Directional and cooperative spectrum occupancy measurements in the 2.4 GHz ISM band

M. Matinmikko, M. Mustonen, M. Höyhtyä, T. Rauma, H. Sarvanko, A. Mämmelä

International Journal of Autonomous and Adaptive Communications Systems 01/2014.

DOI: 10.1504/IJAACS.2014.067239

### Receiver structure and estimation of the modulation index for tamed frequency modulated (TFM) signals

Markku Kiviranta and Aarne Mämmelä

Physical Communication, vol. 10, pp. 61-71, March 2014.

DOI: 10.1016/j.phycom.2013.11.012

### Scaling network information services to support HetNets and dynamic spectrum access

Esa Piri and Henning Schulzrinne

Journal of Communications and Networks, vol. 16, no 2, April 2014.

DOI: 10.1109/JCN.2014.000031

### An autonomous QoE-driven network management framework

Janne Seppänen, Martín Varela, Aggeliki Sgora

Journal of Visual Communication and Image Representation, Volume 25, Issue 3, April 2014.

DOI: 10.1016/j.jvcir.2013.11.010

### Spectrum sharing using Licensed Shared Access (LSA): The concept and its work flow for LTE-Advanced networks

M. Matinmikko, H. Okkonen, M. Palola, S. Yrjölä, P. Ahokangas, and M. Mustonen

IEEE Wireless Communications, Vol. 21, Issue 2, April 2014.

DOI: 10.1109/MWC.2014.6812294

### TACT: A transfer actor-critic learning framework for energy saving in cellular radio access networks

R. Li, Z. Zhao, X. Chen, J. Palicot, H. Zhang

IEEE Trans. Wireless Commun., Vol. 13, No. 4, Apr. 2014.

DOI: 10.1109/TWC.2014.022014.130840

### Cellular architecture enhancement for supporting European Licensed Shared Access (LSA) concept

M. Mustonen, T. Chen, H. Saarnisaari, M. Matinmikko, S. Yrjölä & M. Palola,

IEEE Wireless Communications, Vol. 21, Issue 3, June 2014.

DOI: 10.1109/MWC.2014.6845047

### Interruption probability of wireless video streaming with limited video lengths

Antti Anttonen and Aarne Mämmelä

IEEE Transactions on Multimedia, June 2014.

DOI: 10.1109/TMM.2014.2306656

### Predicting Spectrum Occupancies Using a Non-Stationary Hidden Markov Model

X. Chen, H. Zhang, A. B. MacKenzie, and M. Matinmikko

IEEE Wireless Communications Letters, Vol. 3, No. 4, Aug. 2014.

DOI: 10.1109/LWC.2014.2315040

### SoftMobile: Control Evolution for Next Generation Heterogeneous Mobile Networks

T. Chen, H. Zhang, X. Chen, O. Tirkkonen

IEEE Wireless Communications Magazine, December 2014.

DOI: 10.1109/MWC.2014.7000974

### Towards 5G: When Explosive Bursts Meet Soft Cloud

X. Zhou, Z. Zhao, R. Li, Y. Zhou, T. Chen, Z. Niu, H. Zhang

IEEE Network Magazine, November 2014.

DOI: 10.1109/MNET.2014.6963799

### 7.3 Scientific journal and magazine articles (mid-2015)

#### **Integrating WMN based mobile backhaul with SDN control**

Kari Seppänen, Jorma Kilpi, and Tapio Suihko

Mobile Networks and Applications, Vol. 20, Issue 1, Feb. 2015. DOI: 10.1007/s11036-015-0574-7

#### **Achievable transmission capacity of cognitive radio networks with cooperative relaying**

Tao Jing, Wei Li, Xiuying Chen, Xizhen Cheng, Xiaoshuang Xing, Yan Huo, Tao Chen,

Hyeong-Ah Choi and Taieb Znati

EURASIP Journal on Wireless Communications and Networking, March 2015.

DOI: 10.1186/s13638-015-0311-8

#### **Cognitive Network Management Framework and Approach for Video Streaming Optimization in Heterogeneous Networks**

Tiia Ojanperä, Markus Luoto, Mikko Majanen, Petteri Mannersalo, and Pekka T. Savolainen

Wireless Personal Communications - Early Access – Published online, March 2015.

DOI: 10.1007/s11277-015-2519-7

#### **Energy-efficiency oriented traffic offloading in wireless networks: A brief survey and a learning approach for heterogeneous cellular networks**

Xianfu Chen, Jinsong Wu, Yueming Cai, Honggang Zhang, and Tao Chen

IEEE Journal on Selected Areas in Communications, Vol. 33, No. 4, April 2015.

DOI: 10.1109/JSAC.2015.2393496

#### **A survey of TDMA scheduling schemes in wireless multihop networks**

Aggeliki Sgora, Dimitrios J. Vergados, and Dimitrios D. Vergados

ACM Computing Surveys, Vol. 47, Issue 3, Apr. 2015. DOI: 10.1145/2677955

#### **An evolution toward cognitive cellular systems: Licensed shared access for network optimization**

Miia Mustonen, Marja Matinmikko, Marko Palola, Seppo Yrjölä, and Kari Horneman

IEEE Communications Magazine, Vol. 53, No. 5, May 2015. DOI: 10.1109/MCOM.2015.7105643

#### **Spectrum and license flexibility for 5G networks**

Adrian Kliks, Oliver Holland, Arturo Basaure, and Marja Matinmikko

IEEE Communications Magazine, Vol. 53, Issue 7, June 2015. DOI: 10.1109/MCOM.2015.7158264

#### **Policy-based and QoE-aware content delivery using Q-learning method**

Olli Mämmelä, Faqir Zarrar Yousaf, Petteri Mannersalo, and Johannes Lessmann

Wireless Personal Communications, Vol. 83, Issue 1, July 2015. DOI: 10.1007/s11277-015-2395-1

#### **Energy-efficient dynamic point selection and scheduling method for intra-cell CoMP in LTE-A**

Olli Apilo, Mika Lasanen, and Aarne Mämmelä

Wireless Personal Communications, available online, July 2015.

DOI: 10.1007/s11277-015-2953-6

#### **User-centric versus network-centric load balancing: How to provide good QoE for gold users**

Olli Mämmelä and Petteri Mannersalo

International Journal of Network Management; Special Issue: Advances in Management of Multimedia Services, Volume 25, Issue 4, pages 242–259, July/August 2015. DOI: 10.1002/nem.1893

#### **Optimal base station sleeping in green cellular networks: A distributed cooperative framework based on game theory**

Jianchao Zheng, Yueming Cai, Xianfu Chen, Rongpeng Li, and Honggang Zhang

IEEE Transactions on Wireless Communications, Vol. 14, No. 8, Aug. 2015. DOI: 10.1109/TWC.2015.2420233

#### **Reciprocally opportunistic spectrum access**

Xianfu Chen, Honggang Zhang, Marko Höyhtyä, Mika Lasanen and Jacques Palicot

Transactions on Emerging Telecommunications Technologies. Vol. 26, Issue 8, August 2015. DOI: 10.1002/ett.2810

## 7.4 Doctoral and masters theses

### Cross-layer optimized video streaming in heterogeneous wireless networks

Tiia Ojanperä

Doctoral thesis, University of Oulu. Acta Universitatis Ouluensis. Series C, Technica; Acta Universitatis Ouluensis. Series C, Technica : 453, June 2013.

### Theory of rational decision-making and its applications to adaptive transmission

Adrian Kotelba

Doctoral thesis, University of Oulu, Acta Universitatis Ouluensis, Series C, Technica 460, Sept. 2013.

### Compensation of transmitter nonlinearities using predistortion techniques: case studies of envelope tracking amplifiers and radio-over-fibre links

Atso Hekkala

Doctoral thesis, University of Oulu, Publisher: VTT Technical Research Centre of Finland 2014, VTT Science 53, March 2014.

### Adaptive power and frequency allocation strategies in cognitive radio systems

Marko Höyhtyä

Doctoral thesis, University of Oulu, Publisher: VTT Technical Research Centre of Finland 2014, VTT Science 61, September 2014.

### Improving heterogeneous wireless networking with cross-layer information services

Esa Piri

Doctoral thesis, University of Oulu, Acta Universitatis Ouluensis, C Technica 529, May 2015.

### Tunable lumped-element bandpass filters for cognitive radio application

Tatiana Pavlenko

Master's thesis, Lappeenranta University of Technology, 2013.

### Integrated passive radio frequency filter and multiplexer designs

Joose Rajamäki,

Master's thesis, Aalto University, School of Electrical Engineering, May 2014, 148 pp.

## 7.5 Book chapters

### **Mobile communications and need for CR**

U. Loewenstein, M. Matinmikko

In: Cognitive Radio Policy and Regulation: Techno-Economic Studies to Facilitate Dynamic Spectrum Access. Signals and Communication Technology, 2014. Springer, 79 – 84.

### **ITU-R scenarios**

Miia Mustonen, Marja Matinmikko

In: Cognitive Radio Policy and Regulation: Techno-Economic Studies to Facilitate Dynamic Spectrum Access. Signals and Communication Technology 2014. Springer, 50 – 53.

### **The role of standards in the development of new informational infrastructure**

V. Fomin, M. Matinmikko

In: Systems and Software Development, Modeling, and Analysis: New Perspectives and Methodologies. IGI Global (2014), 149 – 160.

### **Scenarios for CR deployment: Visions from research projects**

M. Matinmikko, J. Paavola

In: Cognitive Radio Policy and Regulation: Techno-Economic Studies to Facilitate Dynamic Spectrum Access. Signals and Communication Technology 2014. Springer, 69 – 75.

## 7.6 Conference publications and presentations (2013)

### **Reciprocal learning for cognitive medium access**

Xianfu Chen, Zhifeng Zhao, David Grace, and Honggang Zhang  
In Proc. IEEE WCNC, Shanghai, China, April 2013.

### **On the Selection of Guard Period and Cyclic Prefix for Beyond 4G TDD Radio Access Network**

Eeva Lähetkangas, Kari Pajukoski, Gilberto Berardinelli, Fernando Tavares, Esa Tirola, Ilkka Harjula, Preben Mogensen, and Bernhard Raaf  
In Proc. European Wireless conference 2013, Guildford, UK, Apr. 2013.

### **QoE-driven network management for real-time over-the-top multimedia services**

Janne Seppänen, Martin Varela  
In Proc. IEEE WCNC 2013, Shanghai, China, 7 - 10 April 2013.

### **Evaluation of autonomic load balancing in wireless multiaccess environment**

Teemu Rautio, Markus Luoto, Jukka Mäkelä, Petteri Mannersalo  
In Proc. IEEE WCNC 2013, Shanghai, China, April 2013.

### **Innovative MEMS-MMIC Components for Agile Antenna Frontends**

L. Baggen, W. Simon, M. Arias Campo, R. Malmqvist, T. Vähä-Heikkilä, B. Grandchamp, P. Rolland  
In Proc. IEEE EUCAP, Gothenburg, Sweden, Apr. 2013.

### **Environmental Friendly Mobile Radio Networks: Approaches of the European OPERA-Net 2 Project**

M. Lasanen, M. Aubree, C. Cassan, A. Conte, J. David, S. E. Elayoubi, T. Galkin, V. Grigore, S. Le Masson, J. Lees, H. Louahlia-Gualous, D. Marquet, Z. Mokhti, L. Nuaymi, H-O. Scheck and L. Smalen  
In Proc. ICT 2013, Casablanca, Morocco, May, 2013.

### **Geometrical bounds on the efficiency of wireless network coding**

Petteri Mannersalo, G.S. Paschos, L. Gkatzikis  
In Proc. WiOpt 2013, 13 - 17 May 2013, Tsukuba Science City, Japan.

### **ENVIRAN: Energy efficient virtual radio access networks**

Adrian Popescu, Haesik Kim, Franco R. Davoli, Raul Dopico Lopez, Somsai Thao, Javier Del Ser, and Gerhard Wunder  
In Proc. WPMC, Atlantic City, NJ, USA, June 2013.

### **Improving energy efficiency in green femtocell networks: A hierarchical reinforcement learning framework**

Xianfu Chen, Honggang Zhang, Tao Chen, and Mika Lasanen,  
In Proc. IEEE ICC 2013, Budapest, Hungary, June 2013.

### **Measurements and Analysis of Spectrum Occupancy with Several Bandwidths**

Marko Höyhtyä, Janne Lehtomäki, Joonas Kokkonemi, Marja Matinmikko, and Aarne Mämmelä  
In Proc. IEEE ICC 2013 - Signal Processing for Communications Symposium, Budapest, June 2013.

### **Selective mapping technique using sliding weighting factor in frequency domain**

Haesik Kim  
In Proc. IEEE VTC Spring 2013, Dresden, Germany, June 2013.

### **Multihop relaying for local area access**

Olav Tirkkonen, Eeva Lähetkangas, Kari Pajukoski, Esa Tirola, and Ilkka Harjula  
In Proc. IEEE VTC Spring 2013, June 2013.

### **The Distribution of Link Distances in Distributed Multiple-Input Multiple-Output Cellular Systems**

Olli Apilo, Mika Lasanen, Sandrine Boumard, and Aarne Mämmelä  
In Proc. IEEE VTC Spring, Dresden, June 2013.

**Modified MUSIC algorithm for DoA estimation using CRLH leaky-wave antennas**

Henna Paaso, Aarne Mämmelä, Damiano Patron and Kapil R. Dandekar

In Proc. CrownCom'13, Washington DC, United States, July 2013.

**Combinatorial auction based channel allocation in cognitive radio networks**

Wei Zhou, Tao Jing, Wei Cheng, Tao Chen, and Yan Huo

In Proc. CROWNCOM 2013, Washington, DC, United States, July 2013.

**On the TDD subframe structure for beyond 4G radio access network**

Eeva Lähetkangas, Kari Pajukoski, Esa Tiirola, Ilkka Harjula, and Jaakko Vihriälä

In Proc. Future Network and Mobile Summit, Lisbon, Portugal, July 2013.

**Network and service governance for the management of future networks**

Beatriz Fuentes, Eleni Patouni, Teemu Rautio, Evangelos Kosmatos, Roi Arapaglou, and George Katsikas

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**On the design of discovery patterns for half-duplex TDD nodes operating in frame-based systems**

Esa Tiirola, Bernhard Raaf, Eeva Lähetkangas, Ilkka Harjula, and Kari Pajukoski

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**Cross-layer Optimized Delivery for Interactive Multimedia Healthcare Services: The CONCERTO Architecture**

L. Bokor, G. Panza, J. Vehkaperä, L. Iacobelli, E. Piri, M. Mazzotti, B. Lecroart, and M. Martini

In Proc. Future Network & Mobile Summit 2013, Lisbon Portugal, July 2013.

**Reciprocity Inspired Learning for Opportunistic Spectrum Access in Cognitive Radio Networks (Invited Paper)**

Xianfu Chen, Tao Chen, Wei Cheng, and Honggang Zhang

In Proc. CROWNCOM 2013, Washington DC, United States, July 2013.

**A QoE-driven adaptation scheme for video content delivery in LTE networks**

Dimitrios J. Vergados, Aggeliki Sgora, Angelos Michalas, Laulainen Jukka-Pekka, Dimitrios D. Verdagos and Yuming Jiang.

In Porc. ISWCS 2013, Ilmenau, 27 - 30 Aug. 2013.

**Full duplex relaying for local area On the Selection of Guard Period and Cyclic Prefix for**

Ilkka Harjula, Risto Wichman, Kari Pajukoski, Eeva Lähetkangas, Esa Tiirola, Olav Tirkkonen

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**DoA estimation through modified unitary MUSIC algorithm for CRLH leaky-wave antennas**

Henna Paaso, Aarne Mämmelä, Damiano Patron and Kapil R. Dandekar

In Proc. PIMRC'13, London, United Kingdom, Sept. 2013.

**Improved design of a CRLH leaky-wave antenna and its application for DoA estimation**

D. Patron, H. Paaso, A. Mämmelä, D. Piazza, and K. R. Dandekar

In proc. IEEE APWC, Turin, Italy, Sept. 2013.

**Combined learning for resource allocation in autonomous heterogeneous cellular networks**

Xianfu Chen, Honggang Zhang, Tao Chen, and Jacques Palicot

In Proc. IEEE PIMRC'13, London, Sept. 2013.

**Combined Learning for Energy Efficiency in Heterogeneous Cellular Networks**

Xianfu Chen, Honggang Zhang, and Mika Lasanen

In Proc. IEEE PIMRC'13: Workshop on End-to-End Green Cellular Networks (Green Cellular'13) London, Sept. 2013.

**Learning Based Proactive Handovers in Heterogeneous Networks**

Seppo Horsmanheimo, Niwas Maskey, Heli Kokkoniemi-Tarkkanen, Lotta Tuomimäki, and Pekka Savolainen  
MONAMI 2013, Cork, Ireland, Sept. 2013

In Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering. Springer International Publishing ( 2013), pp. 57 – 68.

**Relative QoS provisioning over next-generation networks**

Gianmarco Panza, Sara Grilli, Esa Piri and Janne Vehkaperä  
In Proc. IEEE WiMob 2013, Lyon, Oct. 2013.

**Evaluation of Interdependencies between Mobile Communication and Electricity Distribution Networks in Fault Scenarios**

Seppo Horsmanheimo, Niwas Maskey, Lotta Tuomimäki, Heli Kokkoniemi-Tarkkanen, and Pekka Savolainen  
In Proc. IEEE ISGT Asia, Bangalore, India, Nov. 2013.

**Integrated Passive Device process for high quality factor passive components and modules**

Tauno Vähä-Heikkilä, Jan Sajets, Jan Holmberg, Pekka Rantakari, Hannu Ronkainen and Reijo Tuovinen  
In Proc. European Microwave Conference 2013, Nurnberg, Germany, Oct. 2013.

**A 0-Level Packaged RF-MEMS Switched Wideband GaAs LNA MMIC**

A. Gustafsson, C. Samuelsson, R. Malmqvist, S. Seok, M. Fryziel, N. Rolland, B. Grandchamps, T. Vähä-Heikkilä and R. Baggen  
In Proc. European Microwave Conference 2013, Nurnberg, Germany, Oct 2013.

**RF-MEMS Reconfigurable GaAs MMICs and Antennas for Microwave/MM-Wave Applications**

R. Malmqvist, R. Jonsson, C. Samuelsson, A. Gustafsson, S. Reyaz, D. Dancila, A. Rydberg, B. Grandchamp, S. Seok, M. Fryziel, P.-A. Rolland, P. Rantakari, M. Lahti, T. Vähä-Heikkilä and R. Baggen  
IEEE Semiconductor conference CAS 2013, Sinaia, Romania, Oct. 2013, (Invited presentation).

**A Tool for Assessing Interdependency of Mobile Communication And Electricity Distribution Networks**

Seppo Horsmanheimo, Niwas Maskey, Heli Kokkoniemi-Tarkkanen, Pekka Savolainen, and Lotta Tuomimäki  
In Proc. IEEE SmartGridComm 2013, Vancouver, BC, Canada 21 - 24 Oct. 2013.

**On Software-defined Networking for Rural Areas: Controlling Wireless Networks with OpenFlow**

Sami Ruponen  
IEEE EAI AFRICOMM 2013, November 2013, Blantyre, Malawi, Blantyre, Malawi, Nov. 2013.

**Real-time Communication over Wireless Sensor Network – A Prototype for Disaster Areas**

Sarantorn Bisalbutra and Elisa Jimeno  
IEEE EAI AFRICOMM 2013, Blantyre, Malawi, Nov. 2013, Blantyre, Malawi, November 2013.

**Enhanced quality adaptation strategies for scalable video**

Mikko Uitto, Janne Vehkaperä  
In Proc. ISSPIT 2013, Athens, Dec. 2013.

## 7.7 Conference publications and presentations (2014)

**Cell Coverage Area Information Service to Improve Cell Selection in HetNets**

Esa Piri  
In Proc. IEEE CCNC 2014, Las Vegas, USA, January 2014.

**Hierarchical management architecture and testbed for mobile video service optimization**

T. Ojanperä, M. Luoto, M. Uitto & H. Kokkoniemi-Tarkkanen.  
In Proc. CNC workshop of ICNC 2014, February 3-6, Honolulu, HI, USA, 2014.

**Comparison of two frameworks for implementing cognitive network functionality: DDE and OSGi**

T. Ojanperä, A. Karalič, M. Luoto & B. Cestnik

In 33rd Conference on Organizational Science Development - FOCUS 2020, March 19-21, Portoroz, Slovenia, 2014.

**Multilayer 3D LTCC and IPD integration platforms and components from RF to Millimeter Wave Applications**

Tauno Vähä-Heikkilä and Markku Lahti,

In International Wireless Symposium, Xian, China, March 2014. (Invited presentation).

**Reinforcement Learning Method for QoE-aware Optimization of Content Delivery**

Faqir Zarrar Yousaf, Olli Mämmelä and Petteri Mannersalo

In Proc. IEEE WCNC, Istanbul, Turkey, 6-9 April 2014.

**Dual-circular polarised patch antenna array on LCP for 60 GHz millimetre-wave identification**

Antti Lamminen, J. Aurinsalo, J. Säily, T. Karttaavi, J. Francey, and T. Bateman

In Proc. EuCAP 2014, The Hague, The Netherlands, 6-11 April 2014.

**Business models for mobile network operators in Licensed Shared Access (LSA)**

P. Ahokangas, M. Matinmikko, S. Yrjölä, M. Mustonen, H. Posti, E. Luttinen & A. Kivimäki

In Proc. IEEE DySPAN, McLean, VA, 1-4 April 2014.

**Live field trial of Licensed Shared Access (LSA) concept using LTE network in 2.3 GHz band**

M. Palola, M. Matinmikko, J. Prokkola, M. Mustonen, M. Heikkilä, T. Kippola, S. Yrjölä, V. Hartikainen, L. Tudose, A. Kivinen, J. Paavola & K. Heiska

In Proc. IEEE DySPAN, McLean, VA, 1-4 April 2014.

**Description of Finnish Licensed Shared Access (LSA) Field Trial Using TD-LTE in 2.3 GHz Band**

M. Palola, M. Matinmikko, J. Prokkola, M. Mustonen, M. Heikkilä, T. Kippola, S. Yrjölä, V. Hartikainen, L. Tudose, A. Kivinen, J. Paavola, K. Heiska, T. Hänninen & J. Okkonen

In Proc. IEEE DySPAN, McLean, VA, 1-4 April 2014.

**On proving recoverability of smart electrical grids**

S. Horsmanheimo, M. Kamali, M. Kolehmainen, M. Neovius, L. Petre, M. Rönkkö, P. Sandvik

In: Julia M. Badger, Kristin Yvonne Rozier (Eds.), 6th International Symposium, NFM 2014, Houston, TX, USA, April 29 - May 1, 2014.

**Cooperative Business Models in Future Mobile Broadband**

P. Ahokangas, M. Matinmikko, I. Atkova, L. F. Minervini, S. Yrjölä & M. Mustonen

6th Workshop on Coopetition Strategy - "Coopetition Strategy and Practice", Umeå, Sweden, 22-23 May 2014.

**Cognitive Wireless Access Selection at Client Side: Performance Study of a Q-learning Approach**

Olli Mämmelä, Petteri Mannersalo

In Proc. IEEE/IFIP NOMS 2014, May 2014.

**Security Pairings using Physical Layer Properties of Wireless Communications**

Jani Suomalainen, Antti Evesti, Adrian Kotelba

International Conference on Privacy & Security in Mobile Systems, Aalborg, Denmark, May 2014.

**Reducing video interruption probability with cooperative heterogeneous networks**

A Anttonen and A. Mämmelä

In Proc. IEEE Vehicular Technology Conference, Seoul, Korea, May 2014.

**QoE-based Management of Medical Video Transmission in Wireless Networks**

T. Ojanperä, M. Uitto and J. Vehkaperä Janne

In Proc. IEEE/IFIP QCMan14, Krakow, Poland, May 5-9, 2014.

**Cognitive Wireless Access Selection at Client Side: Performance Study of a Q-learning Approach**

O. Mämmelä, P. Mannersalo, In Proc. IEEE/IFIP Network Operations and Management Symposium (NOMS), Krakow, Poland, 5-9 May 2014.

**Reconfigurable antenna based DoA estimation and localization in cognitive radios: Low complexity algorithms and practical measurements**

A Hakkarainen, J. Werner, N. Gulati, D. Patron, D. Pfeil, H. Paaso, A. Mämmelä, K. Dandekar, and M. Valkama In Proc. CROWNCOM 2014, Oulu, Finland, June 2014.

**Considerations on the Licensed Shared Access (LSA) Architecture from the Incumbent Perspective**

M. Mustonen, M. Matinmikko, M. Palola, S. Yrjölä, J. Paavola, A. Kivinen & J. Engelberg  
In Proc. CrownCom 2014, Oulu, Finland, 2-4 June 2014.

**Business Scenarios for Incumbents in Licensed Shared Access (LSA)**

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In Proc. CrownCom 2014, Oulu, Finland, 2-4 June 2014.

**Defining “Co-Primary Spectrum Sharing”— A new Business Opportunity for MNOs?**

P. Ahokangas, K. Horneman, H. Posti, M. Matinmikko, T. Hänninen, S. Yrjölä & V. Gonçalves  
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**Licensed Shared Access (LSA) trial demonstration using real LTE network**

M. Palola, T. Rautio, M. Matinmikko, J. Prokkola, M. Mustonen, M. Heikkilä, T. Kippola, S. Yrjölä, V. Hartikainen, L. Tudose, A. Kivinen, J. Paavola, J. Okkonen, M. Mäkeläinen, T. Hänninen & H. Kokkinen  
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**Measurements and Analysis of Spectrum Occupancy in the 2.3-2.4 GHz band in Finland and Chicago**

M. Höyhtyä, M. Matinmikko, X. Chen, J. Hallio, J. Auranen, R. Ekman, J. Röning, J. Engelberg, J. Kalliovaara, T. Taher, A. Riaz & D. Roberson  
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**Global spectrum observatory network setup and initial findings**

T. Taher, R. Attard, A. Riaz, D. Roberson, J. Taylor, K. Zdunek, J. Hallio, R. Ekman, J. Paavola, J. Suutala, J. Röning, M. Matinmikko, M. Höyhtyä & A. Mackenzie  
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**Incentives for incumbent spectrum users in Licensed Shared Access (LSA): A dynamic capabilities view**

P. Ahokangas, M. Matinmikko, L. F. Minervini, S. Yrjölä, V. Gonçalves & M. Mustonen  
In Proc. EUCNC 2014, Bologna, Italy, 23-26 June 2014.

**Advanced Physical Layer Techniques for 5G**

Haesik Kim,  
CISIS/InfoTech 2014, Dalian, China, 19-21 June 2014. (Invited speech)

**Trade-offs between compression, energy and quality of video streaming applications in wireless networks**

Kamiar Radnosrati, D. Moltchanov, Y. Koucheryavy  
In Proc. IEEE ICC 2014, Sydney, NSW, Australia, 10 - 14 June 2014

**Recent licensed spectrum sharing development in research and regulation in Europe and US: The incumbent spectrumusers perspective**

Miia Mustonen, Marja Matinmikko, Marko Höyhtyä  
In Proc. ICSSC 2014, San Diego, CA; United States, 4 August 2014.

**Energy Efficient Virtual Radio Access Networks for Public Safety**

Haesik Kim  
In Proc. The 32nd AIAA International Communications Satellite Systems Conference, 4-7 August 2014.

**Power consumption trade-off between power amplifier OBO, DPD, and clipping and filtering**

Sandrine Boumard, M. Lasanen, O. Apilo, A. Hekkala, et al.

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**Exponential Companding and Active Constellation Extension Comparisons for PAPR Reduction**

Atso Hekkala, S. Boumard, M. Lasanen

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**Performance Evaluation of Band AMC Using Dynamic Band Selection**

Haesik Kim

In Proc. WPMC, Sydney, Australia, Sep. 2014.

**Greenly offloading traffic in stochastic heterogeneous cellular networks**

Xianfu Chen, Tao Chen, Celimuge Wu, and Mika Lasanen

In Proc. IEEE CCS, Rhine River, Germany, Sep. 2014.

**Massive Multi-User MIMO using DFT spreading for antenna mutual coupling and interference**

Haesik Kim

In Proc. ICTC 2014, Busan, South Korea, Oct. 2014.

**Integrating WMN based mobile backhaul with SDN control**

Kari Seppänen, Jorma Kilpi, Tapio Suihko

In Proc. SDWN 2014, 27 October 2014, Rome, Italy

**Feasibility study of utilizing mobile communications for smart grid applications in urban area**

S. Horsmanheimo, N. Maskey, L. Tuomimäki

In Proc. IEEE SmartGridComm 2014, Nov. 2014, Venice.

**Analysis of Latency for Cellular Networks for Smart Grid in Suburban area**

N. Maskey, S. Horsmanheimo, L. Tuomimäki

In Proc. IEEE PES Innovative Smart Grid Technologies (ISGT) European 2014 Conference, Istanbul, October 12-15 2014.

**QoS Provisioning by Cross-Layer Feedback Control**

G. Panza, S. Grilli, E. Piri and J. Vehkaperä

In Proc. IEEE SCVT 2014, Delft, November 10, 2014.

**Active Antenna System for Cognitive Network Enhancement**

M. Heikkilä, T. Kippola, J. Jämsä, A. Nykänen, J. Keskimäula & M. Matinmikko

In Proc. IEEE CogInfoCom 2014, Vietri sul Mare, Italy, 5-7 November 2014.

**Active Antenna System (AAS) capabilities for 5G systems: A field study of performance**

M. Heikkilä, T. Kippola, P. Kärsämä, A. Nykänen, P. Tuuttila, M. Matinmikko

In Proc. 1st International Conference on 5G for Ubiquitous Connectivity, Levi, Finland, Nov. 2014.

**Cost comparison of Licensed Shared Access (LSA) and MIMO scenarios for capacity growth in Finland**

M. Katsigiannis, A. Basaure, M. Matinmikko

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**Incentives for the key stakeholders in the hybrid use of the UHF broadcasting spectrum utilizing supplemental downlink: A dynamic capabilities view**

Yrjölä, S.; Ahokangas, P.; Matinmikko, Marja; Talmola, P.

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**Evaluation of recent spectrum sharing models from the regulatory point of view**

M. Mustonen, M. Matinmikko, D. Roberson, D, and S. Yrjölä.

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**Assessment of channel interference for Licensed Shared Access (LSA) in the 2.3-2.4 GHz band**

E. Luttinen, M. Matinmikko, M. Katz

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