Background and Mission

The Wireless Communication Systems Group (WICS) consists of four research groups operating at the Department of Communications Engineering and in the Centre for Wireless Communications at the University of Oulu: Communication Signal Processing (CSP), Radio Access Technologies (RAT), Networking (NET), and Wireless Systems (WS). Currently, WICS employs approximately 130 research and teaching staff members, and operates with a total budget of approx. €8.5 million, 72% of which comes from external funding sources.

The mission of WICS is to conduct world-class research, train world-class graduates, create new technology and IPRs, and support society by transferring technology to practical usage. WICS is widely perceived as a forerunner in its field, and a valued partner for research cooperation. Much of its success is due to WICS’ capability to react fast to the changes taking place in the operational environment, as well as to the needs expressed by its research partners. As a provider of high-quality university training, WICS aims at producing theses and dissertations, and peer-reviewed publications of the highest rank.

In essence, WICS is an extremely international research and working environment with 46% of its staff of non-Finnish origin, including two full-time and three part-time professors. WICS runs Masters and Doctoral level training in Wireless Communications Engineering, and has seven doctoral trainees (from five countries) studying on the CWC International Double Degree Doctoral programmes.

As a highly important form of international cooperation, a new research institute was launched in 2011. 

**Scientific Progress**

In 2012, WICS was running 54 research projects with external research funding, including 12 projects with international funding, whereas in 2011 the number of projects was 46. The results of intensive project work resulted in 43 peer-reviewed international journal papers, and 80 peer-reviewed international conference papers published in 2012. The year was also successful from the perspective of academic degrees, as 6 doctoral students of WICS defended their theses.

In this section, scientific progress is presented following the organisational structure of WICS. Based on the WICS mission statement and strategy, fundamental research is conducted on Signal Processing for Wireless Systems, Radio Access Networks and Future Wireless Internet, as portrayed in Figure 1. The research groups concentrating on these are introduced in the following.

![Figure 1. Fundamental research.](image-url)
Communication Signal Processing (CSP)

Data rates, as well as quality of service (QoS) requirements for a rich user experience in wireless communication services are continuously growing. More and more devices will be connected to the global ubiquitous information network, with the Wireless World Research Forum’s (WWRF) vision of seven trillion wireless devices serving seven billion people by 2020. The diversity of the devices and services will increase. While the demand for high data rates to provide multimedia services, like video transmission, is increasing, the demand for low rate sensor information to enable location and context awareness of the services is also growing. However, the current networks cannot provide all the transmission capabilities needed by the emerging services.

To enable the vision, the network control and technology applied in the nodes and devices need to make major leaps. One of the key concerns is the overall power and energy consumption of the devices and the whole network infrastructure. Energy efficiency is a major issue from the battery and device operation perspective, but it also relates to sustainable development where the complete system is concerned. Therefore, in addition to the more conventional target of bandwidth efficiency and increasing the data rates, also the power and energy efficiency of the evolving wireless systems is of major concern. The issue is complicated due to the fact that the infrastructure and user devices have also a cost, both in terms of financial expenditure and usage of natural resources, which implies a certain carbon footprint. Hence, the technical solutions need to be kept simple enough to be versatile for wireless portable devices under ever increasing cost pressure.

The relevant issues of high data rates, energy efficiency and spectral efficiency necessitate the scrutiny of physical and higher layer processing, as well as new solutions for transceiver design and implementation. Communication Signal Processing (CSP), and its subgroup, known as the Radio Engineering Group (RE), are working on finding new solutions to enable the development and construction of energy and bandwidth efficient versatile wireless data networks and network nodes.

One of the main capacity boosters on the physical layer is the use of multiple antennas, both/either in a transmitter and/or in a receiver. This results in a so-called multiple-input-multiple-output (MIMO) radio channel, as opposed to the conventional single-input-single-output (SISO) radio channel. Combined with orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) for downlink (DL) and single-carrier frequency division multiple access (SC-FDMA) for uplink (UL), MIMO technology has been the key physical layer technology for 3GPP Long Term Evolution (LTE) and its Advanced version (LTE-A).

The MIMO technology can be used to boost both the performance and data rate of a single link as well as of the whole system, by applying multiuser MIMO processing. In a particular system level coordination, e.g., via a coordinated multipoint (CoMP), processing is of particular interest and bares significant potential. These technologies, among others, are the enablers for the service targets, given the power and energy constraints. Figure 2 portrays the elements of a MIMO-OFDM system.

The CSP group develops transceiver algorithms and their implementations for MIMO systems, and thus provides relevant scientific information on general inter-node interference management between network nodes, such as user terminals, base stations and relays that have limited backhaul signalling capability to exchange control information with each other. These are used in controlling the interference or managing the radio resources.

Interference level and power/energy consumption also depend heavily on the radio frequency (RF) and antenna design in the devices. The user is always in physical contact with the mobile terminal, and often the antenna is covered by the user’s hand. Even above 90% of the radiated power may be lost due to the absorption of the human hand and head. Thus, it is important to find solutions to decrease the human absorption. The radiation efficiency can be improved significantly by using diversity antenna structures which have been one of the key research topics. During the past few years, the RE group has focused especially on frequency tunable antennas, textile antennas, wideband single and multi-element antennas, wideband diversity and MIMO antennas for mobile terminals, and the effect of user vicinity on the antenna performance, as well as Ultra Wideband (UWB) on-body antennas for medical applications.
The advantage of the MIMO system depends on many parameters, for example on the radio channel environment, and the transmitter and receiver antennas. To evaluate the real performance of a MIMO device, testing needs to be done in a realistic and repeatable radio channel propagation environment. MIMO over the air testing (OTA) allows such tests to be performed. The RE group is involved in the development of simulation models that combine MIMO radio link models with realistic antenna models. This will enable understanding of the impact of the antenna model on the system and the device performance. The group has also developed an efficient dual-polarized wideband (0.7-6 GHz) antenna for the test environment. The MIMO OTA test environment was implemented in 2012 in the anechoic chamber and first measurements were done in order to evaluate measurement accuracy in different test configurations. Both simulation and experimental studies are important for the on-going standardization work of MIMO terminal test methods.

During the last few years, context-awareness has been the pivot of research for many European and international projects in which novel technologies (algorithms, network architectures, protocols, etc.) have been developed to demonstrate the feasibility of context-aware wireless communications. This has been stimulated by both operators as well as service providers, who see “positioning” as the key component to enable novel services. However, while until recently the research has been mainly focused on the design of novel localization and tracking (LT) algorithms for accurate position information, lately it has started to become evident that in many applications, context awareness can and should be understood in a broader sense than mere coordinate information. Indeed, it is expected that a whole new class of services will be introduced by extending the concept of context to semantic information, history and user-identity. All this opens up the opportunity to initiate the investigation of novel LT algorithms capable of exploiting the different types of context-data available, e.g. channel spread, receiving power, delay, congestion level, to improve and increase the number of services offered by the wireless operators. In this regard, the CSP group is actively participating in the EU FP-7 BUTLER project, to which it contributes by designing novel heterogeneous localization solutions and algorithms for behaviour modeling.

The core research areas of the Communications Signal Processing (CSP) and Radio Engineering (RE) Research Group in 2012 included transceiver algorithms and architectures, computation platforms, multiuser MIMO processing and resource allocation in evolving cellular systems, statistical inference and communication for sensor network, antenna design and positioning technologies. Some of the core results in 2012 were:

- new hardware based and programmable implementations of MIMO equalizer and decoding baseband processing for uplink and downlink
- new radio resource management solutions for decentralized interference control and coordination in cellular networks including methods robust to channel estimation inaccuracy and long term energy-efficiency
- interference management and co-existence results for satellite and hybrid terrestrial satellite links and networks
- source-channel coding and iterative decoding algorithms
- new scheduling and resource allocation algorithms for LTE-A systems and their hardware realization
- MIMO over the air testing (OTA) simulation models that combine MIMO radio link models with realistic antenna models
- development of an efficient dual-polarised wideband (0.7-6 GHz) antenna for the MIMO OTA test environment
- application of positioning information for context aware communication and service provisioning in smart cities in the EU FP7 BUTLER Project

Radio Access Technologies (RAT)

Wireless technologies have experienced major cycles of development in the past twenty years or so: introduction of digital transmission schemes, e.g., in GSM, attempts to drastically improve voice capacity via the introduction of CDMA to cellular systems, changing voice oriented cellular systems to mobile internet for consumer markets in the case of 3G cellular, etc. Most recently, broadband wireless data systems have been further developed for mobile cellular users both in WiMAX and 3G-LTE based systems, concentrating especially on improvements in data rates, system capacity and agility. During the course of the development work, the radio transmission schemes over one link have almost reached the information theoretic Shannon-bound. The next target is IMT Advanced (IMT-A), aiming at over 100 Mbps data rates for mobile users.

Although the development of cellular systems has been fast, the underlying network topology has not changed drastically in the past two decades. In today’s 3G-LTE concept, the basic cellular network architecture with centralized control is still dominating. The on-going ITU-R process to define IMT-A sets heavy expectations upon novel ideas for radio spectrum sharing. Experts agree that the ever increasing demands for future wireless systems can only be met by fully optimising the existing radio and network resources by means of decentralised radio access network control, i.e. localised decision-making. Consequently, it is necessary to combine the fast growth of spectral efficiency with radically new physical layer approaches, and new innovative architecture paradigms.

New solutions are mainly sought from self-organized and locally optimized networking concepts; more energy efficient networking architectures, as well as intelligent radio resource management and user scheduling schemes. In parallel, new wireless networking concepts have been introduced, including the extension of multi-antenna concepts to the so-called coordinated multi-antenna transmission and reception. In this approach, relay nodes are expected to improve the range and to reduce interference in macro-cellular environments. In addition, femtocells have been suggested for local capacity maximization in hierarchical cellular networks. These act as just a few examples of the work in progress. Simultaneously, the use of Internet is
becoming increasingly mobile, which revolutionizes the use of mobile wireless technologies.

Hence, it is essential that the development of mobile cellular networks is closely linked with the study of the **future Internet** as a backbone technology for global communication and trade, providing a ubiquitous information infrastructure of the future networked society dependent on billions of devices. The expected transformation offers great opportunities, but also poses enormous challenges. As future networks – and the content shared in them – will become more dynamic and more aware of their surroundings, user co-operation and information exchange will eventually outmanoeuvre server-based information acquisition.

Due to the dynamic nature of future network utilization, centralized control must be gradually replaced by **intelligent context aware network control**. Cognitive radio systems have emerged as potential enablers of a more efficient use of communication resources in future wireless networks. Context and content awareness are essential features of these systems, enabling them to autonomously adapt to their operational environment, internal state, as well as user and service requirements. The system adaptation is controlled by a cognitive decision making algorithm (cognitive engine), which also needs to include some form of learning capabilities, i.e. it must learn from its experiences. In the most simple case, the learning algorithm is implemented as a data base where the past situations and performance metrics are stored; they can then be accessed and used as a reference for decision making.

As first crucial steps in research on cognitive radio systems, some of the key functionalities have been studied in the RAT research group, including sensing of the most important radio environment parameter - the allocation of radio spectrum. Based on spectrum measurements, the radio system can locate vacant spectrum slots, and opportunistically switch its own operation frequency to free bands. The required cognitive algorithms for decision making are extremely complicated due to the number of dynamic variables they need to take into account in their adaptation and in reacting on the system level. Therefore, the research started with rather simple resource allocation and sharing cases, where the cognitive system tries to make use of the available resources. Currently, more complicated scenarios are being addressed, where more than one independent system competes for existing resources. Alternatively, cooperation can also occur between these systems whereby they spontaneously – without human intervention – decide the most efficient manner of sharing the free resources.

Research on cognitive radio systems and cooperative systems has enormous potential as it provides innovative solutions for more efficient utilization of network resources. Recently, the interest in cooperation between mobile terminals has led research efforts towards so-called mobile clouds. Depending on the applications and the type of network content that the mobile cloud members are accessing, cooperative behaviour can result in notable savings of battery and bandwidth usage. The key questions that are currently being addressed include the formulation of metrics and criteria for creating mobile clouds, and assuming the application scenarios and device capabilities, e.g. the number of different wireless links they possess. Also the actual processes by which these clouds are formed and by which their dynamics are managed are under intense research.

Most often the opportunistic characteristics of wireless networks are studied mainly from the point of view of user co-operation and frequency spectrum agility. However, to grasp the full potential of opportunistic features, the concept should be extended to the utilisation of the spatial domain, user location and context information, the existence of several access technologies, knowledge of channel statistical behaviour, traffic pattern knowledge including long-term monitoring and prediction, network topology awareness in mobile device, etc.

In the multitude of interconnected systems, future wireless communications will comprise of a set of different access technologies and cellular radio access technologies featuring base station co-operation, relaying, multi-hop, and hierarchical networks deploying different kinds of base stations. Local connectivity with relatively short links (femtocells and wireless sensors) will gain increasingly more importance and will be integrated as a vital part of future mobile cellular networks. The joint optimization and design of the overall network paradigm poses remarkable challenges and opens significant opportunities due to various system requirements, essentially from large area coverage to sensors and from broadband mobile to low rate sensors.

The fight against climate change is on-going on all fronts of society. The ICT sector is also expected to do its share by cutting energy consumption, and thus reducing greenhouse gas emissions. Simultaneously, wireless broadband communications is becoming a major contributor to the total volume of the ICT industry. Therefore, provision of environmentally sustainable and cost-efficient broadband wireless services is an inevitable target. Regarding base stations and other fixed network infrastructure, the energy savings can be enormous on the global scale. Bandwidth adaptation, discontinuous transmission, cell deployment optimization, green scheduling, and MIMO muting are examples of techniques that can assist in reaching the energy efficiency goals. Portable device users, on the other hand, have a direct incentive in supporting green technology as it can improve their user experience, e.g., through extended battery lives and thereby less frequent charging intervals.

Figure 3 illustrates one candidate structure for an energy and spectrally efficient future wireless network. The main idea here is to decouple system information and user data, and thereby redefine the cell concept. All mobile stations (MS) receive system information as broadcast transmissions. MS, is configured to receive data from a MIMO capable cell provided by BS,. MS operates in CoMP cell that is formed by three base stations BS,. BS, and BS,. MS is served by a cell with an omnidirectional antenna pattern (BS,). Base stations BS, BS, and BS, are idle and not used even for system information in this example. CoMP and MIMO cells are set up when a high data rate is required.
Examples of key topics in future network management and control that were studied in 2012 are given in the following list:

- analysis of a self-organizing heterogeneous network: infrastructure, coexistence and management
- interference management for heterogeneous networks
- energy efficiency on small cell deployment
- performance evaluation for LTE-A based femto deployment
- moving relay enhancements for LTE-A
- physical layer network coding for device-to-device communication
- performance and energy efficiency analysis of full-duplex schemes
- 1000x capacity boost for IMT-A
- robust optimization techniques for RA problems with channel uncertainties
- cross-layer network optimization for delay tolerant applications: from the optimal (centralized) solution towards distributed (possibly suboptimal) implementations
- power-throughput trade-off in a multi-antenna enabled heterogeneous environment

The major achievement of the RAT group in 2012 included an international award and a new major EU project. RAT researchers were internationally awarded for the pioneering research activities in the EU FP7 IP project EARTH “Energy Aware Radio and Network Technologies” which combined the efforts of 15 research partners in 10 European countries. The EARTH consortium received the 2012 “Future Internet Award” for achieving unprecedented energy efficiency in wireless communications networks by creating an integrated solution that allows decreasing energy consumption in particular in 4G/LTE (Long-term Evolution) base stations which account for the highest energy consumption in the mobile network. The major contribution of RAT researchers in EARTH was the development of energy-efficient multi-antenna resource allocation schemes and future system architectures. The research had major relevance for the development of the Energy Efficiency Evaluation Framework (E³F) that judges the impact and energy saving potential of the technical solutions developed in the project. In November 2012, RAT researchers started intensive research work in the most important EU FP7 project METIS “Mobile and wireless communications Enablers for the Twenty-twenty (2020) Information Society” laying the grounds for 5G technologies. The essential input of Oulu-based researchers is mainly related to indoor propagation measurements, channel modelling, new wave form and multiple access design, and studies in massive multiantenna system concepts. METIS is a consortium of 29 partners combining the forces of telecommunications manufacturers, network operators, the automotive industry and academia.

**Networking (NET)**

The increasing usage of Internet and the demand for new services with higher quality will create major challenges in the near future. As different networks become more and more interdependent, their joint optimization becomes crucial as the networks are expected to provide more efficient solutions resulting in better performance and a lower cost of operation. Also, recent advances in the development of low-cost wireless Internet coupled sensor platforms open up opportunities for novel wireless sensor network applications, along with increasing security threats that require intensive attention. Finding solutions to these problems necessitates an approach that jointly optimizes several core functionalities of networking and thus interconnects both theoretical modelling of the system and limitations set by the functional devices operating in the network.

To answer these demands, networking research concentrates on developing new methodologies and concepts around the evolving wireless Internet. These include the optimization of the utility of networks through layered network architecture, as well as complementing the existing solutions on the physical layer by building up a new generation of wireless communications. The research topics include: network optimization; opportunistic network coding as an alternative to conventional routing concepts; inter-cell interference aware resource management; game theory based solutions; the introduction of active network elements (mobile agent traffic optimization); and topology control and security issues in wireless networks. In 2012, special interest has been paid to multi-operator specific management and developing the incentives for multiple operator to cooperate in joint radio resource schemes. Macro and micro economic models have been developed within the WiFiUS projects. Opening the new NEWCOM project will further enable the NET researchers to cooperate with a number of European research institutes (mainly universities) on these problems.

The Networking group runs a number of research projects that cover research topics needed for the optimization of the pending 5G and future 6G wireless networks. More specifically, these include research on: multi-hop transmission, cooperative diversity, network coding, two dimensional MAC protocol, multi-operator cooperation, channel de-fading in adjusting the network topology, Inter System Networking, and phantom networks where the links in the networks are temporarily available.

A second research theme in this area is related to the security of eHealth. Recent technology advances make it possible to monitor medical appliances such as insulin pumps and heart pacers remotely, greatly decreasing the need for personal doctor visits. Naturally, remote wireless monitor-
The third research area is related to enhancing the core network capacity by studying protocols of the fixed Internet. Currently, radio system evolution is taking place with LTE-A both in research and in the standardization (3GPP, ITU-R) which calls for related research on the network aspects. The objective is to explore the connectivity layers of the system, for example on the part of the future LTE network, which provides the efficient packet transport and mobility support for the applications and end-user services accessed over the LTE and LTE-Advanced radio systems. New network concepts must be produced for meeting the future requirements of the evolving LTE and LTE-A radio technologies, as well as for supporting the evolution of the Evolved Packet Core network of the 3GPP as an end-to-end system. Possible solutions are being sought by studying network architecture, mobility and routing, packet transport, traffic management, network management and engineering, and techno-economic issues. Integration of mobile and multi-homed femtocells to the future telecommunications systems is another area of research.

**Wireless Systems (WS)**

Wireless systems research is targeting new technologies and product solutions for the customers of WICS. The five research areas include future cellular systems, dependable wireless networking, cognitive radio systems, wireless security and defence systems and look for emerging technologies, as is indicated by Figure 4.

In the future cellular system domain, a test system for LTE-A is being implemented, where the target is to provide an environment in which manufacturers of equipment can test their products against verified system parameters. Also more targeted designs for LTE-systems have been carried out, especially for providing solutions to advanced capacity boosting antenna designs.

The future trend globally is to include a radio interface in completely new applications and appliances which will
further boost business, as well as research and development activities. Short range wireless communications research focuses on developing novel communication architectures and algorithms for radio networks that have a limited communication distance of less than around one hundred meters. The main research interests lay in wireless sensor networks (WSN) and their numerous applications. WSN network architecture can be based on different topologies, such as a star, cluster tree or mesh network, and typically multi-hop routing is supported to increase the coverage area. In many cases, a WSN can be formed as an ad hoc network, i.e. without any fixed infrastructure. In addition, the target is to improve the energy consumption of sensor nodes, as well as of the whole network, while maintaining the targeted quality of service (QoS).

A WSN can be based on different kinds of nodes that may utilize several radio standards (heterogeneity). For instance, the network can be scalable in the number of nodes and traffic, or it can include various detector types. One feature for WSN installation is good cost efficiency if compared to the corresponding installation utilizing cables as a transmission media. Battery-enabled operation makes it also possible to install WSN nodes to places which cannot be reached by the electricity network, due to which nodes have very low power consumption. This is a great asset, especially for applications designed to be used in locations such as factories, renovated buildings, border control areas, etc. In order to get the optimal performance according to the selected criteria, the requirements of the whole system concept need to be taken jointly into account from the start. This means that research cannot focus, for example, on physical layer solutions only, but all the demands and interactions up to the final application need to be considered throughout the process.

One target of research in the WS research group is to create dependable wireless networks to support the vast variety of requirements of different types of applications. To offer services for ubiquitous access to all needed data, dependable networks are able to ensure reliable and robust communication by utilizing jointly operating sub-networks, without suffering from disturbance from other existing systems/networks. There are several applications where dependable WSN can provide additional value, such as disaster management, surveillance, diagnostics and process control. These partly overlap with topics studied under the umbrella of wireless medical communications (WiMeC) research in which information and communication technology (ICT) is applied to medical requirements. Specifically, the wireless body area network (WBAN) is of current interest at the WS research group.

Research on WiMeC and related applications requires multi-disciplinary co-operation to serve the needs of the community in the best possible manner. The research work that has been carried out for several years already, includes an engineering approach from different university departments, but also requires active discussions with medical experts and personnel of the Centre for Health and Technologies (CHT). This cooperation is expected to create novel solutions for remote monitoring of human physiological signs for use both in and outside hospitals, and hence to decrease the workload of hospital staff in the coming years. The key element in WiMeC research is WBAN, and especially the IEEE802.15.6 standard which was published in February 2012. The standard specifies the signal structure, while allowing free implementation of the receiver and its algorithms, leaving plenty of space for further research in receiver design. The recent research has focused on performance studies of various kinds of receivers using both IEEE802.15.4a as well as IEEE802.15.6 standards. Studies also involve WBAN radio channel modelling and medium access methods, as well as WBAN compatible on-body antenna design. WiMeC research at CWC is also highly international as it involves the active participation of a Finland Distinguished (FiDiPro) Professor and a FiDiPro Fellow, both funded by Tekes. In 2012, funding was also received from Tekes for the strategic project “Information processing and transmission chain for medical applications” (ICMA) which combines the research efforts of WICS, the Department of Computer Science and Engineering, and the Department of Medical Technology. During 2012, the “Individualised Connected Health” (INDICO) project was also launched, coordinated by CHT, where the WS research group explores mobile cloud utilization for healthcare.

Another essential application area for WSN research relates to surveillance and structure monitoring using hierarchical, event-based wake-up radio architecture. This type of solution is expected to produce a scalable heterogeneous wireless network architecture which can be customized for numerous use cases, such as area surveillance monitoring, medical ICT or building/industrial automation. The solution is also able to provide low power consumption due to the intelligent wake-up functionalities. Furthermore, the network architecture is adjustable with radio technologies and detector types, and therefore also adapts to different traffic characteristics. Figure 5 presents the hierarchical layers of a network, with its distributed functionalities as an example.

To gain a better understanding of theoretical research results produced in WS research projects, an experimental WSN research environment has been developed in 2011-2012 using funding from the research infrastructure development funds of the University of Oulu. The test environment is utilised especially in WSN and WiMeC research, but it is also available for all other research groups needing an experimental test-bed suitable for different
kinds of demonstrations and validation. It is also expected that the CWC WSN test-bed opens new doors for new joint research projects with external partners globally.

The development and usage of WSNs in a wider scale became an essential research topic as the outcomes of previous wireless security and defence systems research, conducted in numerous EU and European Defence Agency (EDA) funded projects, was partly merged with WSN research resulting in an extended research approach. Tekes funding was received in 2012 for two small strategic opening projects; SMARTIC (Roadmap to a smart Arctic specialization) which is a University level joint project, and PROTECTOR (a dependable communication and sensor system for the critical infrastructure of PROTECTiOn and Rescue) realised in cooperation with the Tampere University of Technology and the Finnish Geodetic Institute.

For several years already, cognitive radio systems research has been carried out and the results have been piloted with a cognitive radio networking demonstrator, based on a Linux Enriched (LE)-WARP programmable radio platform that can be configured to build experimental and reconfigurable wireless networks. Various use scenarios and trials for cognitive networking are being implemented and verified with the platforms. One example of the demonstrated technologies includes load balancing, by cognitive actions, of cellular system traffic to other available frequency bands to alleviate traffic congestion when it happens. These demonstration activities have been realised in the CORE project, and are continued in the CORE+ project in the Tekes TRIAL programme devoted for the development of cognitive trial environments.

Emerging technologies include themes where small scale activities are starting. During the reporting period, wireless optical communications research activities have been launched. The solutions may be very attractive in indoor environments for two reasons – high bandwidth offering high data rates, and the fact that radio frequency operation is avoided as weak signals are pointing according to the customer’s desire to reduce some radio emissions.

The research results of the Wireless Systems research group can be utilised in R&D work aiming at new technologies and product solutions in a number of potential areas including:

- **Future Cellular Systems**: LTE and LTE-Advanced; Beyond 4G; and Femtocells
- **Dependable Wireless Networking**: WiMeC, Disaster Prevention and Recovery ICT; Smart Energy Grids ICT; and Vehicular Communications
- **Security and Defence Systems**: Tactical Communication Systems; Tactical Positioning Systems; and Radar and Signal Intelligence Systems
- **Cognitive Radio Systems**: Novel Applications for Agile Wireless Systems; Introducing Cognitivity to Standard Systems; and Test Environments for Cognitive Networking
- **Emerging Technologies**: Wireless Optical Communications; and Nano-scale Communications

Some of the major achievements of the WS research group in 2012 were:

- the organisation of the UWBAN Workshop in conjunction with Bodynets 2012 in Oslo, Norway
- two demonstrations on cognitive radio technology:
  1. Demonstration of the benefits of cooperative offloading in cognitive radio networks in 12th FRUCT conference in Oulu in November 2012
  2. Cognitive radio demonstration at ECC/ETSI/COST TERRA workshop in May 2012 in Mainz, Germany
- an innovation disclosure on novel wake-up radio implementation

### Personnel

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### External Funding

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### Doctoral Theses


### Selected Publications


Cai S, Matsumoto T & Yang K (2012) SIMO channel estimation using space-time signal subspace projection and soft informa-


