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 120 research and teaching staff members and operates with a total budget of approx. € 7.7 million, 83% 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 44% of its staff of non-Finnish origin, including three 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. **Wireless Innovation between Finland and US (WiFiUS)** is an institute created for long-term research and education collaboration between Finland and the USA in the field of wireless communications. In Finland, the functions of the institute are coordinated by the Department of Communications Engineering, which also has a major role in conducting research within five of the six joint projects of the institute. The WiFiUS is a virtual institute and it combines the research efforts of three Finnish universities with a counterpart team of eight universities and research institutes in the USA. It is founded by the Finnish Funding Agency for Technology and Innovation (Tekes), the Academy of Finland, and USA’s National Science Foundation (NSF). The aim of the institute is to create solutions to the challenges which growing wireless communication, with large increases in capacity needs, sets on existing networks. New approaches to the research of cognitive networks, as well as resource and spectrum utilization are being used in solving the challenges of the continuous growth in wireless traffic. The international collaboration in WiFiUS leverages the synergies and resources for research and education in the two countries in order to accelerate the rate of generating research innovations and the development of talent and workforce. The institute provides means for sharing expertise with emerging experimental platforms, standards and wireless technology policies and facilitates, and supports interaction between academia, industry and government agencies. It employs a number of activities including a web portal that provides services and content to participants, physical and virtual PI meetings as well as student investigator meetings, yearly summer schools and graduate student exchange.

Scientific Progress

In 2011, WICS was running 46 projects with external research funding, whereas in 2010 the number of projects was 41. The results of intensive project work resulted in 48 peer-reviewed international journal papers, and 99 peer-reviewed international conference papers published in 2011. The year was also highly successful from the perspective of academic degrees as 7 doctoral students of WICS defended their theses.

In this section, scientific progress is presented following the organizational 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 is continuously growing. More and more devices will be connected to the global ubiquitous information network, with the Wireless World Research Forum’s (WWRF) [http://www.wireless-world-research.org/] 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. The 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 back-haul 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 depends 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, and that has been one key research topic. During the past few years, the RE group has especially focused on frequency tuneable and multi-frequency antennas, textile antennas, wideband single and multi-element antennas, wideband diversity and MIMO antennas for mobile terminals, the effect of user vicinity on the antenna performance and antennas for medical applications.

The advantage of the MIMO system depends on many parameters, for example on a radio channel environment, and transmitter and receiver antennas. To evaluate the real performance of a MIMO device, testing needs to be done in a realistic 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 the understanding of the impact of the antenna model on the system and device performance. The group is also developing efficient antennas for the test environment.

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 modelling.

The core research areas of the Communications Signal Processing (CSP) and Radio Engineering (RE) Research Groups in 2011 included transceiver algorithms and architectures, computation platforms, multiuser MIMO processing and resource allocation in evolving cellular systems, antenna design and positioning technologies. Some of the core results in 2011 were:

- New hardware based and programmable implementations of MIMO equalizer and channel estimation baseband processing for uplink and downlink
- New radio resource management solutions for decentralised interference control and coordination in cellular networks including novel channel state acquisition methodology and over-the-air optimization of transceivers
- MIMO technologies for satellite and hybrid terrestrial satellite links and networks
- Source-channel coding and iterative decoding algorithms and related theoretical framework
- Wideband and diversity antenna structures for both mobile terminals and measurement purposes, including the compensation of human hand and head absorption
- Development of a MIMO OTA measurement system
- Design of novel LT algorithms for positioning, some of which have been tested with real low data rate (LDR) ultra-wideband (UWB) devices during the final demonstration of the EU FP7 EUWB project

Some highlights of the year include the student paper award for the paper “Zero-forcing spatial interweave with greedy scheduling” by J. Kaleva, P. Komulainen & M. Juntti published at the International Symposium on Wireless Personal Multimedia Communications (WPMC 2011) in Brest, France in October 2011.

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 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 with the 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 macrocellular 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 surround-
ings, 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 autonomously – 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 at 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.

![Figure 3. Potential future wireless network configuration.](image-url)
Examples of key topics in future network management and control that were studied in 2011 are given in the following list:

- network and radio resource management for standalone and networked femtocells
- distributed algorithms for macro-femtocell interference management
- energy efficiency on small cell deployment
- performance evaluation for LTE-A based femtocell deployment
- moving relay enhancements for LTE-A
- advanced relaying schemes for mobile networks
- wireless sensor mobile networks fusion
- 1000x capacity boost for IMT-A
- public safety and LTE
- cross-layer design for video transmission over wireless networks
- decentralized cross-layer network optimization
- cross-layer network optimization for delay tolerant applications
- delay-tolerant networks

**Networking (NET)**

The increasing usage of Internet and demand for new services with higher quality 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 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 optimisation); as well as topology control and security issues in wireless networks.

The Networking group runs a number of research projects that cover research topics needed for optimization of pending 5G 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 the medical appliances such as insulin pumps and heart pacers remotely, greatly decreasing the need for personal doctor visits. Naturally, remote wireless monitoring of such crucial appliances, including those embedded in human bodies poses several formidable technological challenges which include security of data communication, device authentication, attack resistance, and seamless connectivity. A remote monitoring protocol must be executed in a resource-constrained environment with energy efficiency. The recently specified Host Identity Protocol (HIP) could solve most of the security issues of remote appliance monitoring. However, it has to be developed to run in an embedded device environment; its security properties must be triple-checked against the stringent requirements; potential privacy issues must be addressed; and protocol messages and cryptographic mechanisms must be adopted to wireless sensor standards. Although bearing high risks of provable security and patient faith, remote monitoring of health appliances could create breakthroughs in healthcare cost reduction, and bring great benefits for individuals and the society.

Another area of networking research is the Internet-of-things. Traditional security techniques used in the Internet today, e.g. IKEv2 with IPsec or TLS, are not ideal for use with constrained M2M devices or networks. Furthermore, they pose scalability challenges when deploying large M2M systems. Recent adaptation to IETF protocols called Diet HIP is aimed at M2M applications. This among other novel optimizations to DTLS, IPsec and IKEv2 is explored by the Networking group. To be more precise, the work focuses on security aspects of embedded web services on sensor nodes. Available alternatives for node- to-server security protocols including HIP-DEX + IPsec and IKEv2 is explored by the Networking group. To be more precise, the work focuses on security aspects of embedded web services on sensor nodes. Available alternatives for node- to-server security protocols including HIP-DEX + IPsec and DTLS Light will be evaluated and developed.

Energy efficiency and lightweight computation are critical requirements for security. A suitable balance of overhead and protection level needs to be determined. Furthermore, the research team will study congestion control over unreliable transport protocols in sensor networks. During special events, such as a power outage, a large number of sensors could try to transmit their reports simultaneously causing a congestion collapse in the large-scale sensor deployment. Load balancing and server clustering are important to consider here. The researchers are taking part in developing the architecture and protocols necessary for mass-scale M2M services including up to billions of web resources hosted on a billion sensor nodes. The architecture is expected to utilize the Constrained Restful Environment (CoRE) specifications from the IETF. The goal is to provide large-scale web services for the future Internet-of-things. There are several strategically key technical challenges still remaining in applying CoRE technology to massively scalable M2M applications. These include analysis and optimization of the scalability of the protocol, dealing with congestion control on a network scale (rather than the traditional flow approach of TCP), and applying sufficient yet efficient security mechanisms for M2M. Finally, to make M2M platforms useful for Web application developers, we need to understand the customer.
and developer requirements for making use of M2M. As response to the above challenges, the project partners are responsible for developing an emulation test-bed providing up to a billion node networks to estimate the scalability of protocols and architecture.

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 lookout for emerging technologies as is indicated by Figure 4.

![Wireless Systems (WS)](image)

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 research and development activities. One target of research in WS is to create dependable wireless networks to support a 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 utilising 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 medical information and communication technology (ICT), and specifically the wireless body area network (WBAN); these are all of current interest at WS.

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. The WSN network architecture can be based on different topologies, such as 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. 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. 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 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.

Research on medical ICT 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. This cooperation is expected to create novel solu-
tions 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 medical ICT research is WBAN, and especially the IEEE802.15.6 standard which will be published shortly. 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 the existing IEEE802.15.4a standard, which is also useful for WBAN applications. Studies also involve WBAN radio channel modelling and medium access methods, as well as IEEE802.15.6 compatible on-body antenna design. Medical ICT 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 2011, funding was also received from the Marie Curie International Research Staff Exchange Scheme supported by the European Commission which facilitates active researcher exchange in the next four years.

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 WSN 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 get a better understanding of theoretical research results produced in WS research projects, an experimental WSN research environment is under construction with funding from the research infrastructure development funds of the University of Oulu. The test environment will be used especially in WSN research, but it is also available for all other research groups needing an experimental test-bed suitable for different kinds of demonstrations. It is also expected that the CWC WSN test-bed opens new doors for new joint research projects with external partners globally.

Cognitive radio systems research is performed also in the radio access technologies theme in which the main interest lies in assessing the practicality of proposed solutions. The results produced so far 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. Currently, various use scenarios and trials for cognitive networking are being implemented and verified with the platforms. Also a cognitive protocol stack and cognitive engine have been implemented on WARP platforms for the networks to be able to independently choose the operating parameters and radio resources to obtain optimal performance. One example of the demonstrated technologies includes off-loading cellular system traffic to other frequency bands to alleviate traffic congestion when it happens. One possible application area for the results is wireless security and defence systems.

Wireless security and defence systems research has been conducted in numerous EU and European Defence Agency (EDA) funded projects. The outcomes of the projects include tactical radio system waveform designs for wideband networking, especially targeted towards land force operations. Also a design of a radio system for operations in an urban environment has been accomplished. Research has also been conducted to provide some key critical solutions for a possible candidate for next generation wideband authorities’ radio system. Other themes include system designs for passive radar systems operating using civilian radio signals as target illuminators as well as providing solutions based on wireless sensor networks for replacing the surveillance capability previously realized with land mines.

Emerging technologies include themes where small scale activities are starting. During the reporting period wireless optical communications were targeted. 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 to customer’s desire to reduce some radio emissions.

The research results of the Wireless Systems research group can be utilised in the 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**: Medical ICT, Disaster Prevention and Recovery ICT; Smart Energy Grids ICT; and Vehicular Communications
- **Cognitive Radio Systems**: Novel Applications for Agile Wireless Systems; Introducing Cognitivity to Standard Systems; and Test Environments for Cognitive Networking
- **Security and Defence Systems**: Tactical Communication Systems; Tactical Positioning Systems; and Radar and
Signal Intelligence Systems

Emerging Technologies: Wireless Optical Communications; and Nano-scale Communications

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Doctoral Theses


Selected Publications


