SMARAD

Activity Report 2011

Centre of Excellence in Smart Radios and Wireless Research

Antti Räisänen (editor)
Contents

1 Introduction to SMARAD

2 Research teams

3 Highlights of SMARAD research in 2011
   - Future Radio and Antenna Systems
   - Cognitive Radio
   - Millimetre Wave and THz Techniques
   - Sensors
   - Materials and Energy

4 Participation in European projects

5 SMARAD funding

6 SMARAD personnel during 2011

7 Visitors to SMARAD

8 Visits from SMARAD to foreign institutes

9 Post-graduate degrees

10 Publications

11 Other scientific activities of SMARAD members
1. Introduction to SMARAD

Centre of Excellence in Smart Radios and Wireless Research (SMARAD)

In 2001 the Academy of Finland appointed SMARAD with the name “Smart and Novel Radios Research Unit” as one of the centres of excellence in research for the period 2002–2007. In 2006 the Academy announced its decision that the renewed SMARAD (“Centre of Excellence in Smart Radios and Wireless Research”) was appointed a Centre of Excellence for years 2008–2013.

According to the Academy: “Centres of excellence are research units or researcher training units which comprise one or more high-level research teams that are at or near the international cutting edge of research in their field. They will also share a common set of objectives and work under the same management. Funding for centres of excellence comes not only from the Academy, but also from the host organisations of the units concerned, and possibly from other funding bodies, such as Tekes, business enterprises and foundations. A centre of excellence may be a unit of research teams working at both universities and research institutes.”

Currently there are altogether 33 Centres of Excellence: the Academy Board has appointed 18 centres of excellence for the national centre of excellence programme in 2008–2013 and 15 for the years 2012–2017.

The current SMARAD was formed in 2006 by the Radio Laboratory, the Electronic Circuit Design Laboratory and the Signal Processing Laboratory of the Department of Electrical and Communications Engineering, Helsinki University of Technology (TKK). After the restructuring of the TKK organization, SMARAD involves research groups from three departments, namely the Department of Radio Science and Engineering, Department of Micro and Nanosciences, and Department of Signal Processing and Acoustics, all within the Aalto University School of Electrical Engineering.

SMARAD provides world-class research and education in RF, microwave and millimetre wave engineering, in integrated circuit design for multi-standard radios as well as in wireless communications. In microwave and millimetre wave engineering it is also the only research unit in Finland. SMARAD is a contributor to MilliLab, ESA External Laboratory (a joint institute between VTT and Aalto University School of Electrical Engineering).

The total number of employees within the research unit is about 90 including about 30 senior scientists and about 40 doctoral students and several students working on their Master thesis. The unit conducts basic research but at the same time maintains close co-operation with industry. Novel ideas are applied in design of new communication circuits and platforms, transmission techniques and antenna structures resulting also in patents and invention reports. ‘Smart’ in SMARAD’s name refers to adaptability of antennas, radio devices, or materials to RF signals or fields.

SMARAD has a well-established network of co-operating partners in industry, research institutes and academia worldwide. It coordinates a few EU projects. The funding sources of SMARAD are also diverse including the Academy of Finland, Tekes, and the Finnish and foreign telecommunications and semiconductor industry. As a by-product of this research SMARAD provides highest-level education and supervision to graduate students in the areas of radio engineering, circuit design and communications through Aalto University and Finnish graduate schools such as GETA.

SMARAD Principal Investigators are:
Prof. Antti Räisänen, chairman: Millimetre wave and THz techniques
Academy prof. Visa Koivunen, vice-chair: Communications and statistical signal processing
Prof. Kari Halonen: Electronic circuit design
Prof. Sergei Tretyakov: Advanced artificial electromagnetic materials and smart structures
Prof. Pertti Vainikainen: RF applications in mobile communications and non-destructive testing
Members of the Scientific Advisory Board of SMARAD are (2011):
Prof. Danielle Vanhoenacker-Janvier, Université Catholique de Louvain (UCL), Belgium
Prof. Björn Ottersten, Royal Institute of Technology Stockholm (KTH), Sweden
Professor Heli Jantunen, Oulu University
Professor, Vice-Rector Heikki Mannila, Aalto University
Dr Ritva Dammert, Aalto University
Dr Kati Sulonen, Academy of Finland
Dr Hannu Kauppinen, Nokia Research Center
Dr Jani Ollikainen, Nokia Research Center

2. Research teams

1. Millimetre wave and THz techniques. The research group is led by Prof. Antti Räisänen. There are 3 other senior researchers with a doctoral degree (Dr. Juha Mallat, Dr. Juha Ala-Laurinaho, and Dr. Dmitri Lioubtchenko) and 6 researchers working towards their doctoral degree. In addition, Prof. Constantin Simovski works part-time in this group.

2. Advanced artificial electromagnetic materials and smart structures. This research group is led by Prof. Sergei Tretyakov. Prof. Constantin Simovski works in this group. The research group includes 3 other senior researchers, and 5 researchers working towards their doctoral degree.

3. RF applications in mobile communications and non-destructive testing. This research group is led by Prof. Pertti Vainikainen. There are 6 other senior researchers with a doctoral degree (Dr. Katsuyuki Haneda, Dr. Jari Holopainen, Dr. Clemens Icheln, Dr. Veli-Matti Kolmonen, Dr. Tommi Laitinen, and Dr. Valeri Mikhnev) and 9 researchers working towards their doctoral degree.

4. Communications and statistical signal processing. The research group is led by Academy prof. Visa Koivunen. Prof. Risto Wichman works full time in this research group. In addition, there are 5 other senior researchers with a doctoral degree in the group. There are 9 researchers working towards their doctoral degree.

5. Electronic circuit design. The research group is led by Prof. Kari Halonen. Prof. Jussi Ryynänen works full time in this research group. The group includes 2 other senior researchers with a doctoral degree and 11 researchers working towards their doctoral degree.

3. Highlights of SMARAD research in 2011

The Centre of Excellence in Smart Radios and Wireless Research, SMARAD, specialises in research into RF, microwave and millimetre wave techniques, integrated circuit design for multi-standard radios as well as wireless communications. Areas of special interest include RF techniques for wireless data communications, radio channel modelling and measurement, new and smart materials and structures, smart (adaptive) antennas, integrated circuit design for multi-standard radios, receiver structures and architectures and the signal processing algorithms they require. The results will have practical application especially in future wireless communication systems. In the following the SMARAD research in 2011 is described under the following titles: Future radio and antenna systems, Cognitive radio, Millimetre wave and THz techniques, Sensors, and Materials and energy.
3.1 Future Radio and Antenna Systems

Future wireless systems demand ever higher data rates and wider bandwidths, and meeting these demands continues to be a challenging and wide research topic ranging from antennas and propagation to system concepts. The future of wireless communications is strongly heterogeneous, where different systems coexist in the same bands requiring highly flexible and reconfigurable transceivers. Moreover, interference management is a major issue since cell sizes are getting smaller, networks may be single frequency networks and network planning may not be feasible in some deployments (e.g. pico-cell and femto-cell deployments). Spectral efficiencies should be improved simultaneously giving rise to different multiple antenna techniques including cooperative MIMO, closed-loop MIMO, multi-user MIMO, as well as diversity transmission schemes for, e.g., evolution of DVB-T/H, DVB-T2 and DVB-NGH.

In addition, future wireless systems require new network topologies characterized by flexible spectrum use and cooperative techniques. So far wireless cellular systems have been optimized for wide area coverage, while WLAN has targeted short-range communications and it lacks mechanisms to support, e.g., mobility, necessary to wide area systems. System architecture for local area communications combining the mobility and services of cellular systems as well as high data rates and autoconfigurability of WLAN would be highly desirable.

Antenna shielding reduces interaction between user and mobile terminal antenna. A new method was introduced to reduce the effect of the hand and head of a user on the operation of mobile terminal antennas at 900 and 2000 MHz. Traditional antenna elements are placed on that side of the mobile handset that points away from the head (in talk position). This way, radiation exposure (SAR) limits are more easily met and the antenna performance is better. However, this kind of antenna configuration is far from being optimal in many other use positions. For instance, when holding the mobile terminal in both hands to browse the internet, the user's fingers may cover the antenna element, reducing the radiation efficiency and causing frequency detuning. In order to more generally decrease the effect of the hand and head on the operation of mobile terminal antennas, a shielded antenna structure that consists of two non-self-resonant antenna elements was designed and evaluated (Fig. 1). Depending on the use position, the better-performing antenna element is selected and the other is acting as a shield. It is shown that the proposed structure can improve the total efficiency with hand and head by 5.0 dB and decrease the maximum specific absorption rate (SAR) in the head by 81% at 900 MHz compared to the traditional single element structure. At 2000 MHz, the benefits are 2.1 dB and 43%, respectively. The shielding structure can be used also to significantly decrease the SAR in the hand.

![Antenna shielding reduces interaction between user and mobile terminal antenna.](image)

Fig. 1: (a) Fabricated shielded antenna prototype, and (b) measurement set-up in RAMS including the phantom hand and the generic SAM head filled with tissue-equivalent liquid.
Effect of the user’s hands on the operation of mobile terminal antennas. During the design of antennas for mobile terminals, the interaction of different antenna parts with the user holding the device and their effect on the performance of lower UHF-band antennas in handheld terminals was studied with simulations and measurements of a prototype antenna. The input impedance, efficiency, and far-field directional pattern of an internal broadband digital television antenna are affected by the presence of the user’s hands. In the worst case, the antenna efficiency decreased by 7–11 dB compared to the free space case as shown in Fig. 2. The results also indicated that the power absorption in the hand(s) is generally more severe for the total efficiency than the change of the matching (detuning of the antenna). On the other hand, it was also shown that in certain cases, the total efficiency of the antenna can even be improved due to the hands of the user. The results clearly increased the understanding of the effect of the user’s hands on the operation of especially the lower UHF-band antennas.

![Fig. 2: Measured total efficiency (left) for the browsing grip (right) of the prototype antenna.](image)

Multi-antenna mobile terminal diversity performance in proximity to human hands under different propagation environment conditions. Instead of increasing the spectral efficiency with the implementation of multi-antenna elements in mobile terminals, antenna designers also have to deal with mutual coupling that depends on the number of antenna elements, as well as to consider the variable effect of the hand on the mobile terminal performance metrics. The grip of the hand is of great importance, especially with the current trend of people holding the terminal using either one or two hands at one time, as shown in Fig. 3. Therefore, there is a need to provide essential information for multi-antenna designers on terminal diversity performance, especially when the diversity terminal is in the proximity to the realistic human hand grips. It is of paramount importance to take into account the distorted radiation patterns due to the human hands beforehand the estimation of the diversity performance. According to our findings: a) The human hands have a negative influence on Effective Diversity Gain (EDG) which is mostly attributed to the dramatic drop of the antenna radiation efficiencies. b) The cross polarization ratio value has important influence on EDGs due to the power imbalance between the partial power gain patterns. c) The effect of the incident wave parameters of the propagation environment on the EDG performance is almost negligible.
Angular and shadowing characteristics of dense multipath components in indoor radio channels. The current geometry based stochastic multiple-input multiple output channel models are parameterized based on radio channel parameter estimates extracted from channel measurement data. In practice, most parameter estimation algorithms used to parameterize these models are based on the plane wave assumption. However, it has been reported that these so-called specular components (SC) capture only a part of the propagated energy, and that also the residual part of the channel, i.e., the dense multipath components (DMC), has a significant impact on the overall propagation channel.

The dense multipath components (DMC) represent the part of the radio channel that cannot be characterized by using the specular components (SC). In this study, the propagation characteristics of the DMC were analyzed in indoor environments based on extensive channel measurements. The results showed that the contribution of the DMC to the total received power can vary as much as between 10% and 95%, being generally higher in non-line-of-sight than in line-of-sight scenarios. Detailed analysis of the power-angular profiles showed that, in all the investigated scenarios, the propagation mechanisms of the SC and DMC have large similarities. Even though the energy is more spread in the angular domain in the DMC than in the SC, the energy in the DMC is, however, clearly concentrated around the same angles as in the SC. The shadowing objects clearly have an effect on both the SC and DMC.

MIMO over-the-air testing. Development of MIMO over-the-air (OTA) test methodology is ongoing. Anechoic chamber and fading emulator based multi-probe test system shown in Fig. 4 is one promising candidate for MIMO-OTA testing. A crucial aspect largely dictating the cost of the test system, the required number of probes for synthesizing the desired fields inside the multi-probe system, has been examined in our work. We have presented rules for the number of probes required for synthesizing the radio propagation channel inside the multi-probe system as a function of the size of the device under test (DUT) in wavelengths and the uncertainty level of the field synthesis using the well-known spherical wave theory.
Calibration procedure for 2-D MIMO over-the-air multi-probe test system. Multi-probe based systems are an attractive alternative for MIMO over-the-air testing of mobile communication devices. Circular 2-D multi-probe systems provide a good means for synthesizing such radio-propagation channel conditions where the incoming fields to the mobile device are plane-wave fields arriving from the horizontal plane. The accuracy of the plane wave field synthesis with multi-probe system suffers from the fact that the probes are located in the near field and, even more importantly, the scattering from the neighbouring probes. This research work is conducted to propose a calibration procedure to partially compensate those near-field and the scattering effects. This calibration procedure is based on two measurement steps and related data processing, which provide the required excitation coefficients for the probes for enabling the partial compensation of the near-field and scattering effects inside the test zone. The proposed calibration procedure is validated by computer calculations.

Figure 5(a) shows the field inside the test zone where both near-field and the scattering is considered without applying any compensation technique and Fig. 5(b) shows the test zone field where the proposed calibration technique is considered. The result validates the proposed calibration technique for partially compensating the near-field and scattering effects in the test zone.

Relays in wireless communication systems. Relays that receive and retransmit the signals between network nodes can be used to increase throughput or extend coverage of networks and facilitate novel network topologies. Relays can be classified into amplify-and-forward (AF) relays and
decode-and-forward (DF) relays. The former ones retransmit the signal without decoding DF relays decode the received signal, encode the signal again, and transmit. From signal processing point of view AF relays offer interesting challenges in terms of cooperation between multiple relays, channel estimation and equalization and utilization of channel state information in multihop networks. Spectral shaping of the transmitted signal requires advanced techniques for digital filter design. DF relays, for one, offer various possibilities to optimize the resource sharing between transmit and receive slots and develop joint encoding and decoding techniques in multiple access systems. Our research develops concepts and analysis for relay enhanced wireless networks.

**Full-duplex communications.** Relays like other wireless transceivers may operate in half-duplex mode, i.e. they do not transmit and receive simultaneously in the same frequency band, or in (in-band) full-duplex mode. The latter operation typically requires a spatial separation between transmit and receive antennas to reduce loop-back interference from the transmit antennas to the receive antennas. Implementation costs of full-duplex transceivers are higher than those of half-duplex ones and their operation range is limited determined by transmit and receive powers and interference levels. On the other hand full-duplex relays may improve system throughput when the transceivers does not require two channel resources for reception and transmission. Gains, however, depend on several system parameters, e.g. the symmetry of the traffic between the network nodes. Full-duplex MIMO transceivers inevitably require adaptive loop interference cancellation techniques in RF domain and digital baseband, the latter being outlined in Fig.6. The transceiver may optimize spatial transmit and receive filters to mitigate loop interference based on different amount of side information on the channels (left), or subtract the estimated interference (right), or combine these two approaches. In addition to algorithm design, the effect of loop interference must be incorporated into analytical performance studies as well. Our research develops concepts and analysis for wireless communication systems consisting of full-duplex network nodes.

![Fig. 6: Loop interference cancellation in spatial domain or subtraction of estimated loop interference.](image)

**Dirty RF.** Building flexible, compact, high-quality, and yet low-cost radio equipments for future wireless systems, is not straightforward. On one hand, re-configurable architecture is required given the heterogeneous radio environment and flexible spectrum use. On the other hand, wide bandwidths together with high data rates would rather require dedicated hardware solutions. We focus on developing deep understanding, how the most essential analog RF impairments, power amplifier nonlinearities, oscillator phase noise, mirror frequency interference due to IQ imbalance, nonidealties in A/D converters, effect the performance of wideband multi-antenna transceivers. The emphasis is on the analytical work to characterize the resulting distortion and their effect on to system performance in closed-form, and to develop digital signal processing algorithms for the mitigation of RF impairments.
**Multiantenna systems.** The goal is to derive transceivers and transmission schemes that exploit all the degrees of freedom in radio channels to achieve high spectral efficiency, high system throughput, extended range as well as powerful interference cancellation capability. In general, practical multiantenna systems require some channel state information in the transmitter, because otherwise interference between different data streams and users becomes too large in the receiver. The main research problem is then to optimize the tradeoff between the system performance and the required feedback information from receivers to transmitters.

In case of cooperative and multipoint MIMO techniques, multiple transmitters simultaneously transmit to a user, which is especially advantageous when the user is located on the edge of the coverage area. With multiuser MIMO techniques the same channel resource is shared with multiple network nodes aiming to further improve the throughput of network. Concerning heterogeneous wireless systems and spectrum sharing, cooperative and multiuser MIMO algorithms should operate in decentralized manner assuming that network nodes possess only limited information on the state of the system. These kind of distributed techniques are further elaborated within wireless sensor networks.

**Distributed and resource efficient parameter estimation in wireless sensor networks.** The objective is to develop distributed detection and estimation schemes for detecting an event and estimating and tracking an unknown common parameter, e.g., temperature, level of water contaminants, or a target position, using multiple displaced sensors. Signal collection through a distributed network of sensor nodes improves robustness of performance and reliability of the network due to redundancy and provides spatial diversity due to multiple viewing angles. In the particular case of sensor networks, the bandwidth and power requirements are closely linked to whether the acquired data is processed in a centralized or a decentralized manner, see Fig. 7. In the former approach, signals from all sensor nodes are processed jointly in one centralized fusion center, thus, facilitating the use of battery operated and low-cost sensors. For a large network, the excessive amount of data can make central processing computationally prohibitive, and may require communications over longer range which leads to reduced battery life. Comparing to the centralized estimation approach, decentralized (or distributed) detection and estimation reduces the amount of data that each estimator needs to process by introducing collaboration between neighboring nodes in the network. Collaboration improves algorithm robustness, e.g., in case of sensor failures; however, it increases bandwidth and power requirements.

As an alternative to classical approaches, this research project aims to develop distributed estimation algorithms with sensors that can make discerning use of received data, thereby providing more informative estimates and thriftier use of resources like power and bandwidth. Thus the nodes should update the parameter estimates only when needed and cooperate only when such an action improves awareness. The amount of data transmitted in a sensor network can be effectively reduced via censoring where data is transmitted only if it is informative. Such algorithms will lead to improved performance, prolonged lifetime for the sensor nodes, and improved reliability of the entire network.
Optimal signal processing for arbitrary array configurations. In this work signal processing techniques for sensor arrays of arbitrary geometry are developed. Signals are processed in azimuth, elevation and polarimetric domains. Optimal, robust and high-resolution techniques are derived and their statistical properties are established. The methods can deal with array nonidealities by incorporating the array calibration data and wavefield modeling in an elegant manner. Conformal arrays and azimuth, elevation and polarimetric data processing may be handled. Hence, the developed methods are applicable in most arrays and applications of practical interest.

Multiantenna systems are becoming seminal part of future communication terminals, navigation receivers, wireless and sensor networks. There are many design constraints, especially in handheld devices such as mobile internet terminals and handheld TV-receivers, and it is rarely possible to build array configurations with nice uniform geometry. Moreover, array elements suffer from nonidealities and mutual coupling. Consequently, there is a need for array processing techniques that allow applying advanced smart antenna algorithms such as optimal beamforming and direction finding, to real-world arrays with arbitrary configuration and array nonidealities. For example, in small handheld devices there are so many design constraints that no regular array geometry can be used.

Novel optimal and robust procedures for array processing using arbitrary array configurations are developed in this work. Analytical performance studies are completed with practical implementations using real world arrays in hand-held terminals. The prototype depicted in Fig. 8 has been implemented in cooperation with Nokia Research center. There is a high performance prototype system for tracking other users carrying RF tags or mobile phones. It has been demonstrated in a good number of international wireless events. Similar principles may be used to develop conformal arrays of arbitrary geometry for beamforming and high resolution direction finding applications in azimuth, elevation and polarimetric domains.
**Fig. 8:** Optimal and computationally efficient array processing techniques may be generalize to arbitrary array configurations by using Fourier transform of the array calibration data and non-trivial manipulation of input-output matrix model for the array data. Practical application of our method: implementation of 2-D antenna array of arbitrary geometry in a mobile terminal and application in direction finding and ranging (Right).

**MIMO radar and novel radar concepts.** Another interesting line of research followed in this research is MIMO radars and waveform diversity. MIMO radars are multistatic radar configurations that provide significant performance gains over classical radar systems. Antennas may be co-located as in traditional phased array systems or they may be widely distributed. Similarly to MIMO communications, spatial diversity (induced by radar cross section) may be exploited. Novel techniques for target detection, high resolution localization and tracking, parameter estimation and accurate time synchronization for distributed MIMO radar are developed. In co-located MIMO radars, different waveforms may be launched from each antenna, see Fig. 9. The possibility of using different probing signals in each antenna provides many benefits in target identification and interference cancellation, for example. Novel methods for parameter estimation, resource allocation and adaptive and optimal waveform design are developed and their performances are analyzed. Additional radar related topics include multicarrier techniques for radar and wireless ranging and radar and detection of vital signs using radar.

**Fig. 9:** Multistatic, MIMO radar configuration using waveform diversity. Virtual aperture may be created using signal processing for designing and optimizing the waveforms launched from each antenna.
High-impedance surface based multi-functional antenna. In this project we have studied the properties of a mushroom-type high-impedance surface (HIS) using reflection-phase calculations for oblique incidence and find two orthogonal resonant modes. An antenna based on a finite-sized HIS has been designed to utilize both of these modes. The first mode provides a dipole-like radiation pattern, and the second one a broadside pattern. Furthermore, the second mode can be coupled to the antenna with a proper coupling element in order to obtain a wide bandwidth. Fig. 10 shows the geometry and S-parameters of the antenna.

Fig. 10: Photo and S-parameters of the designed and tested antenna.

Huygens source antennas. Huygens source antennas are electrically small antennas that radiate unidirectionally and in the ideal case have perfect polarization purity. The proposed antennas are composed of both electric and magnetic dipoles and the polarization of radiation is defined by the orientation and feeding of these dipoles. We have designed practical realizations of such antennas employing chiral particles (for circular polarization) and omega-particles (for linear polarization). The antennas have been studied analytically, numerically, and experimentally, confirming this concept for obtaining electrically small antennas with very useful radiation properties. Fig. 11 shows the designed and tested antenna for linear polarization. Measured directivity pattern shows polarization close to linear in the whole upper half space.

Fig. 11: Conceptual structure (left) and realization (right) of a Huygens antenna for linear polarization.

Electromagnetic cloaking based on waveguiding structures. The cloaking efficiency of a finite-size cylindrical transmission-line cloak operating in the X-band has been verified with bistatic free space measurements (see Fig. 12). The cloak is designed and optimized with numerical full-wave simulations. The reduction of the total scattering width of a metal object, enabled by the cloak, is clearly observed from the bistatic free space measurements. The numerical and experimental results are compared resulting in good agreement with each other.
Metal-plate cloak as an antenna at a lower frequency. Within this project we have found that a transmission-line cloak capable of, for example, hiding a large metal support structure, can also operate as a dipole antenna. The basic transmission-line cloak geometry can be modified so that the cloak structure itself acts as an antenna at a frequency well below the cloaking frequency. The structure retains its cloaking properties despite of these modifications. Two types of cloak-antennas have been proposed: a dipole antenna and a monopole antenna. The operation of these antennas has been verified using simulations and measurements. We have also shown how the antenna resonance frequency can be tuned by changing its geometry. Fig. 13 shows the cloak/antenna geometry and the simulated and measured reflection coefficient.

3.2 Cognitive Radio

This research concentrates on enabling technologies for cognitive radios. Cognition indicates that the radio is capable of learning from the radio environment and adjust its transmission parameters including frequency, waveforms and power. The radio has situation awareness in a sense that it has knowledge of its own capabilities, status of the spectrum in the neighborhood and maybe even the network. Cognitive radio takes an opportunistic view in agile usage of underutilized parts of radio spectrum. Secondary users need to ensure that no harmful interference is caused to primary, incumbent users of the frequency band. Free spectrum is a resource that varies depending on the time, frequency band and location. The primary user may not need the spectrum all the time in all the places. Hence, one could utilize the spectrum much more efficiently by finding idle spectrum
and exploiting it for data transmission while controlling the level of interference caused to other users, see Fig. 14. It is also important to develop power efficient and high fidelity implementations for cognitive radios so that battery operated devices can operate for a long time without compromising their performance.

**Fig. 14:** Flexible use of time-frequency-location varying underutilized spectrum.

**Spectrum exploration and exploitation.** Research in spectrum exploration and exploitation has focused on optimizing identification and exploitation of unused spectrum in a cooperative and distributed manner. Distributed detectors provide diversity gain since they can mitigate shadowing and fading effects. Moreover, user cooperation facilitates fast multiband sensing and improves performance while using simple individual detector structures. The concrete research problems addressed in this work are dealing with decentralized detection of primary users by a group of cooperating secondary, optimal sensing policies for distributed detection by multiple sensors over multiple potentially scattered subbands as well as optimizing cooperative spectrum access policies for them. Optimization is based on trading off between the exploration and exploitation of the spectrum such that sensing is focused on subbands where high quality spectrum is idle persistently, see Fig. 15. As a result, the system learns the dynamic behavior of the spectrum and can maximally exploit identified idle spectrum. Joint optimization and accessing of idle bands is modeled as a restless multiarm bandit problem. These learning methods stem from statistical inference, machine learning and stochastic optimization. Policies for exploring and accessing the spectrum can be optimized jointly. In addition, we have developed methods for modeling and managing interference as well as flexible spectrum usage in device to device communications. This work has been done in cooperation with Princeton University and Nokia Research Center.

**Fig. 15:** Trading off between spectrum exploration and exploitation. Developed greedy spectrum sensing policy allocates sensing to subbands that provide idle spectrum persistently and as a result performance close to ideal sensing policy is achieved.
Implementation issues in spectrum sensing and exploitation. The quality of the spectrum sensor decisions and decision statistics, and the decision frequency are the key parameters in optimization of the spectrum utilization and the overall performance of the cognitive radio system. The most important properties of a single detector entity are, firstly the ability to make the decisions quickly and reliably, and secondly the ability to observe a wide frequency range and multiple primary systems simultaneously. In addition, the implementation must be optimized such that the change of primary signal under detection has as small as possible effect on the receiver front-end parameters. Reconfiguring the front-end takes time and slows down the hopping between different bands and signal types. Spectrum sensing applications also set high requirements for RF hardware (wide bandwidth, wide tuning range, high dynamic range, high linearity), which is a limiting factor in current implementations. Sensing algorithm should be selected so that it enables the flexible configuration of the sensor parameters with software. In order to enable the sensing of multiple systems simultaneously, the functionality of the DSP implementation should be independent of the sampling rate and signal bandwidth of the system to be detected.

While targeting a battery operated application it is of utmost importance to minimize the power consumption of the sensor both at circuit and architectural level. Therefore, in the implementation of a simultaneous multisystem spectrum sensor, one should lead up to a solution in which the amount of hardware does not increase linearly with the number of systems under detection (or even with number of transmit/modulation parameters in a single system). In addition to spectrum sensing functionalities, DSP may have to implement support functions such as additional filtering and gain control. As the functional requirements on the DSP domain increase, it becomes more and more important to optimize the energy and cost efficiency of the realized circuits. While performing spectrum sensing, it might also be beneficial to obtain additional information for example about the adjacent channels and their power levels. For example in some cases, presence of a strong signal on the channel adjacent to the one under detection could affect the reliability of the detection results. In addition, this knowledge could be to adjust RF functions in the receiver.

In hardware side the development of cognitive radio has focused on developing energy efficient RFICs and demonstrating sensing algorithms in various different environments. The demonstrations have focused on defining the limitations of the RF hardware to the detection and detector performance. The over-the-air measurements and the measurements in the controlled environment show that the different nonlinearities in the RF hardware can easily decrease the reliability of the spectrum sensor. In some extent the developed feature detectors can improve the detection reliability when compared to energy detectors. However, still advances in improving the linearity at RF and analog parts must be made to increase the reliability of the spectrum measurements. In the detector side a comprehensive study on different algorithms has been done in addition with algorithm development to find optimal algorithms suited for mobile environment. The focus on algorithm implementation has been on finding implementations that lead to small implementation size together with low power consumption. In RFICs the focus has been on finding solutions that improve the aforementioned RF linearity and also support wide variety of different frequency bands. Fig. 16 illustrates demonstrator board that enables over the air measurements.

White spaces. Secondary usage of TV white-spaces is an emerging application of cognitive radio techniques, where unutilized or underutilized spectrum reserved for digital terrestrial television is allocated to wireless communications. Spectrum sensing can be used to determine the level of TV signals in a specific location, but sensing alone is not able to provide information on the frequency planning of the network, i.e., it is not possible to know whether a particular TV frequency is planned for use in the measured location. Thus, sensing must be complemented with a geo-location database. We develop techniques to improve the secondary usage of TV white spaces by combining the information from geo-location database and radio propagation modeling with measurements from white-space devices.
**Integrated multiband receiver for SAR applications.** The first prototype chip was measured in 2010. The second version of integrated receiver for SAR application was implemented and measured during 2011. The complete integrated SAR receiver, Fig. 17, includes RF- front end, baseband circuits and analog-to-digital (ADC) converter. The RF-front-end has three different bands: L-band, C-band and X-band, and the baseband has two different cut-off frequencies: 160MHz and 50MHz. The ADC has 4 different modes, from 8 bits mode to 5 bits mode.

**Fig. 16:** Detector for spectrum sensing

**Fig. 17:** Implemented SAR receiver.
Intensive measurements have been performed on the second chip. All the individual blocks (the baseband and ADC) were measured separately to verify their functionality and to setup the correct tuning. The circuits design and measurement results of the baseband and ADC has been reported in European Solid State and Circuit Conference (ESSCIRC) in Helsinki on September 2011. Measurement of the whole receiver was done in accordance with the compliance specifications set by ESA. For L-band receiver, the chip has been measured in 3 different temperatures (room temperature, 0°C and 45°C). Measurement in 5 different temperatures (room temperature, 0°C, -25°C, 45°C and 70°C) was performed for the receiver in C-band mode. The final presentation of the project has been delivered on 29th September 2011 at ESA-ESTEC, where also the possibility to use the designed integrated receiver in a future project by a German company was discussed. The circuit design and the measurement results for the whole receiver will be presented in “The Fourth International Workshop on Analog and Mixed Signal Integrated Circuits For Space Applications (AMICSA)” which will be held on 26 - 28 August 2012 at ESA-ESTEC.

**Procedures against impedance detuning of mobile terminal antennas in the vicinity of a user.** If the foreseeable user effects are taken into account already in the antenna design, part of the degradation of the performance in real use cases can be avoided, which was demonstrated in the study. Interaction between a mobile terminal antenna and a hand of a user was investigated with an experimental study using capacitive coupling element antennas and homogeneous anthropomorphically shaped hand phantoms.

Four different capacitive coupling element antennas, shown in Fig. 18, were designed and manufactured. The differences of the performances of the antennas were studied with several hand grips, see Fig. 18. It was confirmed with measurements that antenna element shape, size and location can affect significantly the performance of the antenna in a mobile handset held in a user’s hand. Differences of several dB in total efficiency were observed between different capacitive coupling element based antennas with typical hand grips. Part of the hand effect can be avoided by using a multi-element antenna structure with antenna switching. Shaping the antenna element so that the probability of interaction with the index finger is minimized is worthwhile as well.

![Fig. 18: Effect of the user’s hands on the operation of mobile terminal antennas.](image)

### 3.3 Millimetre Wave and THz Techniques

**Millimetre wave integrated circuits.** An extended version of the power combining CMOS power amplifier was designed and successfully measured. The amplifier achieves +14.5 dBm saturated output power at 90 GHz with a standard 1.2 V supply and occupies an active area of 0.17 mm². The
amplifier is implemented in 65 nm CMOS process taking into account reliability issues related to the voltage swing limitations of the transistor. The chosen amplifier topology also provides ESD-protection. The micrograph of the power amplifier is presented in Fig. 19.

A 100-GHz balanced frequency doubler was designed in 65-nm CMOS technology as well. The simplified schematic and a chip micrograph are presented in Fig. 20. The wideband balancing is realised with an on-chip spiral balun. At 100 GHz the measured conversion loss of the frequency doubler is 16 dB using an input power of +5 dBm. The fundamental suppression is better than 25 dB from 42 to 55 GHz.

In addition, 165 and 183 GHz low noise amplifiers were reported. The amplifier circuits have been manufactured using a 100-nm gate length metamorphic high electron mobility transistor technology. Measured on-wafer performance shows 19-27 dB of gain and lowest noise figure values of 4 dB. A micrograph of one of the 165-GHz low noise amplifiers is presented in Fig. 21.

![Fig. 19: Chip micrograph of the 90-GHz CMOS power amplifier. The area, including pads is 0.42 mm² and the active area is 0.17 mm².](image1)

![Fig. 20: A schematic and a chip micrograph of the 100-GHz CMOS frequency doubler. Chip size is 0.65 mm x 0.42 mm.](image2)

![Fig. 21: Chip micrograph of the 165-GHz metamorphic HEMT low noise amplifier. The circuit area is 2.0 mm² (2.0 mm x 1.0 mm).](image3)
Characterisation, modelling, and applications of nonlinear 2 terminal millimetre wave devices. ESA-related SMARAD and MilliLab research activities for the characterisation of Schottky devices for space and other THz applications have been continued. This research and development area includes various closely related mutually complementing activities that target to combine theory and experimental results in a concrete way, benefitting both academic research as well as industrial applications in the field.

Results from the novel characterisation method of Schottky diodes by using a universal mixer test jig were reported. In addition to the jig for fundamental mixer operation, also a new universal jig designed for subharmonic mixer diode testing is under development. A flexibly usable jig to being adaptive for newest diodes by various manufacturers is in target.

The recent break-through in THz Schottky diode series and thermal resistance extraction has received much attention. The novel method takes holistically into account also important self-heating related effects in submicron-sized diodes. A new step, an accompanying study including fast pulsed diode measurements has been started.

Development of Schottky diode-based demonstrators has produced excellent wide-band devices. The manufactured demonstrators include a monolithic Schottky diode based frequency tripler which has been verified to produce exceptionally wide-band operation covering 75–140 GHz. The state-of-the-art results were obtained with a very small chip-size design, an achievement based on a developed new compact output matching and filtering structure (see Fig. 22a).

Accurate on-wafer scattering parameter measurements with a vector network analyzer (VNA) are important at submm-wave frequencies (Fig. 22b). However, calibration of the on-wafer measurements at submm-wave frequencies is a challenging task. Standard methods utilizing, e.g., the thru-reflect-line (TRL) or line-reflect-reflect-match (LRRM) calibration often have problems with errors caused by cross-talk due to imperfect grounding of the ports. We investigate a new calibration technique based on the 16-term error model.

![Tripler Circuit Diagram](image1)

**Fig. 22:** a) Exceptionally wide-band (75-140 GHz) tripler circuit based on compact output matching design. b) On-wafer vector network analyzer measurements of Schottky-diodes at 100-300 GHz.

**Millimetre wave beam steering with a MEMS-based high impedance surface.** Beam steering with a MEMS-based high impedance surface (HIS) has been studied in W band (80 GHz). The steering mechanism is based on the principle of a phase gradient array. MEMS-based tuneable HIS is a periodic array of unit cells with dimensions much smaller than a wavelength. The reflection phase properties of the unit cell structure are analysed by using a simplified model with appropriate boundary conditions. MEMS tuneable HIS can be used for electronic reflective beam steering by inducing reconfigurable surface impedance via applying different bias voltage to different rows of elements of the MEMS varactor array. A simplified model of a surface with 40 impedance strip
lines of 0.35 x 0.35 mm² unit cells is used for demonstrating the beam steering ability. Radiation pattern of a strip consisting of elements with different impedance is analyzed numerically for beams of normal and oblique incidence. Fig. 23 shows the simulated radiation pattern for the surface which is programmed to steer the beam to direction of 0° while the angle of illumination is 45°.

**Fig. 23:** The normalized radiation pattern at 80 GHz with incident angle from 45° for the surface which is programmed for a beam at the direction of 0°.

**Periodic structures for leaky-wave antennas (LWA).** The periodic structures can be utilized in wide range of applications. Starting with filters, the theory of the periodic transmission lines was developed very well over the time since 1940’s. With onset of metamaterials into the practical engineering and scientific life, possibilities not considered before emerged. By loading a transmission line with the counterparts of its constitutive parts, i.e. by series capacitor and parallel inductor we obtain coupled right/left-handed transmission line (see Fig. 24a). With proper design rules, this transmission line becomes leaky, i.e. the wave propagating along the structure is continuously radiated into the space above the structure (e.g. for planar transmission line as suggested in Fig. 24b). A microstrip based leaky-wave antenna was designed and measured. Scattering parameters measurement shown in Fig. 24c displays the comparison of measured and theoretical reflection of the antenna sample which is out of balance. The precision of design procedures previously suggested by various textbooks on metamaterials or periodic leaky-wave antennas is proving to have strongly deteriorating accuracy with the operation frequency approaching millimeter waves and higher. The parasitic components of the loading elements are strongly influencing overall performance of the composite right/left handed (CRLH) transmission line. Furthermore, the evanescent fields excited at the discontinuities are so strong, that the loading elements interact with each other and their performance strongly depends also on their position within the unit cell (be it unit cell smaller or larger than the one tenth of the guided wavelength). These effects are currently under research and to be described in the future.

**Fig. 24:** a) Unit cell of periodically loaded transmission line, b) continuously radiating microstrip CRLH transmission line, and c) comparison of simulation and measurement for unbalanced LWA.

**Dielectric rod waveguide (DRW) components.** Dielectric rod waveguide is a promising device for transmitting an mm-wave power. DRW has an advantage over conventional metal waveguides of
lower dielectric losses compared to metal losses, especially at frequencies above 100 GHz. Another advantage is the possibility of using standard microfabrication and semiconductor techniques for integrating various components into it. Recently the DRW antenna for 220 – 325 GHz was fabricated and tested. The advantage of such an antenna is its compact size compared to other directive antennas and a good matching with a rectangular metal waveguides. The schematic image of the antenna is shown in Fig. 25a. In Fig. 25b a design of a bolometer power sensor integrated into a DRW is presented. The power sensor measures the amount of power travelling in the DRW.

Using an array of DRW antennas with integrated phase shifters, it is possible to create a controllable phased antenna array. A phase shifter integrated into DRW is shown in Fig. 25c. It consists of electrically small dipoles which are periodically printed on the DRW side wall. Each dipole is loaded with a ferroelectric varactor to control the phase of the propagating wave.

![Schematic view of the DRW antenna](image)

**Fig. 25:** a) Schematical view of the DRW antenna, b) schematical view of the bolometer power sensor structure integrated into a DRW, and c) schematical view of the phase shifting dipole structure integrated with the DRW antenna.

**Integrated lens antennas for beam steering.** An integrated lens antenna provides the means for beam-steering with high directivity. Reduction of internal reflections in low permittivity integrated lens antennas was studied. The reflections are known to cause high side lobes and increased cross-polarization and mutual coupling. A very effective reflection reduction method based on lens shaping was developed and tested with antenna measurements. The designed lens and an example of the measurement results are shown in Fig. 26. The lens was designed using an in-house developed ray-tracing simulation program. The beam-steering properties were tested with radiation pattern measurements at 77 GHz. The new shaped lens was compared to a classical lens design and the reduction of internal reflections was demonstrated with simulations and measurements.

![Lensed antenna](image)

**Fig. 26:** a) A photograph of the designed extended hemispherical lens with shaped extension, and b) measured normalized radiation patterns at 77 GHz.

**Millimetre wave reflectarray.** A 120-GHz reflectarray for mm-wave identification (MMID) or millimeter-wave imaging applications is being developed. The reflectarray has 138-mm diameter and it is fabricated on a silicon wafer. The 3700 elements of the reflectarray compensate the
spherical phase front from the feed in such a way, that the field is refocused at a desired location, at few meters from the reflectarray. The reflectarray elements are based on a conductor-backed coplanar waveguide (CBCPW) structure. There, a patch antenna is coupled to a phase shifter, which introduces the required compensation. The reflectarray is being developed for active control with MEMS phase shifters. In the MEMS, the phase shift arises from shorting a coplanar line with capacitive shunt switches located so that the normalized reflection phase in different states is 0°, −90°, −180°, and −270°. Before the active, static reflectarrays are fabricated with open-ended or short-circuited CPW stub as the phase shifter.

![Reflector array geometry](image)

**Fig. 27:** a) Reflectarray geometry. The reflectarray is offset fed and it can be actively focused with MEMS-actuated phase shifters. b) Phase-shift pattern for a reflectarray focusing to 0.5-m offset at 3-m distance.

Three different types of static reflectarrays are fabricated: 1) focusing to boresight at 3 m, 2) focusing to 0.5 m aside from boresight at 3 m, and 3) focusing to 3-km distance at boresight. All of the reflectarrays are fed with an offset of −27° at distance of 0.3 m (Fig. 27a). Fig. 27b shows the resulting phase shift pattern in case of reflectarray 2. The static reflectarrays are characterized in a near-field measurement range at 120 GHz. Figure 28 shows the measured beam patterns with comparison to simulation as well as the near-field phase of the reflectarray.

![Beam patterns](image)

**Fig. 28:** a) Measured (solid) and simulated (dashed) beam pattern for reflectarray focused 0.5 m aside at 3 m, and b) phase of the $S_{11}$-parameter measured at 1-mm distance from the surface of the reflectarray with an open-ended waveguide.

**Material measurement in the frequency range of 75–325 GHz using a vector network analyser.** The extraction of material parameters at millimetre wavelengths is an interesting and important topic of investigation. A fast, accurate and easy to use method to determine permittivity and loss tangent in the frequency range of 75 to 325 GHz has been developed where the material sample id placed inside a short section of an enclosed transmission line. The line was a section of the rectangular waveguide connected to two ports of a vector network analyzer. The reflection and transmission S-parameters are measured in the frequency band of 75 to 325 GHz to estimate the
permittivity and loss tangent of the material under test. Similar situation is also simulated with a commercial full-wave simulator (HFSS) and comparison is then made between the measured and simulated results. As a reference case this has been done first for Teflon (PTFE), and after that for a sample of unknown polymer.

For Teflon and unknown polymer, the simulated reflection and transmission coefficients for different values of the dielectric constant and loss tangent are compared with the measured coefficients using least square error fitting method. Fig. 29 shows the transmission coefficient ($S_{21}$) phase results obtained from the measurement and simulation. Using least square error fitting method, the best fit is obtained for permittivity of 2.0 and loss tangent 0.003 for Teflon. The permittivity of the unknown polymer is obtained to be 2.4 and loss tangent 0.06.

![Fig. 29: a) Measured and simulated transmission coefficient phase for Teflon and b) measured and simulated transmission coefficient phase for unknown polymer.](image)

**Extraction of electromagnetic material parameters from reflection-transmission coefficients.** In connection to the previous subject, we have also theoretically studied algorithms for extraction of effective material parameters from measured reflection and transmission coefficients. The known methods suffer from an intrinsic limitation related to the electrical thickness of the measured material. In this project we have proposed a novel way to overcome this limitation. Although being based on the classical Nicolson-Ross-Weir (NRW) technique, the proposed extraction technique does not involve any branch seeking and is therefore capable of extracting material parameters from samples thicker than $\lambda/2$, a measure that would otherwise cause problems in the NRW extraction technique. The proposed derivative of the NRW extraction technique has been used to study the effect of thermal noise on the extracted material parameters.

**60 GHz membrane antenna array for beam steering applications.** Beam steering is one of the techniques to overcome the high path loss at 60 GHz. A two element antenna array has been designed and manufactured for the 60 GHz frequency band using micromachining technology. The use of micromachining to remove the substrate material under the antenna elements provides high efficiency and good radiation properties compared to a bulk silicon process at millimeter wave frequencies. The same manufacturing process could be used to manufacture phase shifters based on MEMS switches. However, in this work passive phase shifters using different lengths of transmission lines were used to demonstrate beam steering. The prototypes include antenna arrays with different phase shift values and single antenna elements (Fig. 30). The input impedances of the manufactured antennas were measured using a probe station and a vector network analyzer and the radiation pattern measurements were performed with the 3D on-wafer radiation pattern measurement system located in the Orange labs, la Turbie, France. The manufactured antennas fulfil the -10 dB matching criterion and the maximum measured realized gain is 6.0 dBi. The antennas
were designed in co-operation with University of Nice-Sophia-Antipolis, France and the prototypes were manufactured in LAAS-CNRS, University of Toulouse, France.

Fig.30: A photo of the manufactured antenna prototype.

3.4 Sensors

Microwave visualization of objects buried in non-transparent media. Subsurface radar sensing is aimed at detection, localization and identification of versatile objects in non-metallic media. Among those tasks, detection of pipes, voids, mines in soil, rebars and cracks in civil engineering structures, tumours in biological tissues are worth noting. A new signal processing approach based on expanding the subsurface radar data into separate B-scans for amplitude and phase and their subsequent assembly in the common image using transformations of signal amplitude → intensity of the pixel and signal phase → color of the pixel has been proposed. The idea of the method is based on the fact that amplitude of the wideband signal reflected from the buried object indicates presence of the object at some depth while the phase shift at the act of reflection depends on the contrast of dielectric properties between the object and surrounding medium and therefore can characterize it. Thus, the image where intensity of the pixel is related to amplitude of reflected signal and color to its phase can be used for both detection of the objects and their discrimination. Some results of microwave visualization of objects buried in sandbox using frequency-swept signals in the range of 1.3 to 6.5 GHz and UWB tapered-slot antennas are shown in Fig. 31. As seen in Fig. 31, both detection and differentiation of buried objects is possible with the use of the proposed method.

Fig. 31: a) Void in the sandbox, b) anti-personnel plast mine (PMN) simulant in the sandbox. Ground surface is seen at zero depth, bottom of the box at the depth of 40 cm, objects have been buried at 10 cm.
Design of an ideal phase-conjugating surface as an array of nonlinear and nonreciprocal particles. In our earlier work we have theoretically shown that a pair of phase conjugating surfaces can function as a perfect lens, focusing propagating waves and enhancing evanescent waves. However, the known experimental approaches based on thin sheets of nonlinear materials cannot fully realize the required ideal phase conjugation boundary condition. In this project we have shown that the ideal phase conjugating surface is in principle physically realizable and investigated the necessary properties of nonlinear and nonreciprocal particles which can be used to build a perfect lens system. The physical principle of the lens operation was analysed in detail and directions of possible experimental realizations are outlined. Fig. 32 illustrates conceptual design of phase conjugating particles consisting of two antennas connected via a non-linear circuit.

![Diagram](image)

*Fig. 32: The conceptual design of particles forming an ideal phase-conjugating array. BM = balanced modulator; LPF = low-pass filter.*

MEMS accelerometer. The accelerometer has been designed during the time period of 2010-2011. The block diagram of the sensor is shown in Fig. 33. The sensor interface is implemented with a hybrid topology which combines the open-loop readout and electrostatic damping. The open-loop readout is implemented with a charge balancing topology which has ratiometric output. The electrostatic damping is used to damp the high quality factor Q of the micromechanical sensor element. The ratiometric output is converted to the digital domain by a Delta-sigma ADC. As the output of the ADC is inversely proportional to the supply voltage, the digital output of the sensor is expected to have no supply dependency, in theory. The chip has on board voltage regulator, clock generator, DSP and analog buffer.

The sensor chip has been implemented in a 0.35 μm CMOS process. The micrograph of the sensor chip is shown in Fig. 34. The chip area is 6.66 mm² and the nominal current consumption at 3.6 V supply is 1 mA. The sensor interface is able to damp the high Q of the sensor element confirmed by measurement results and it achieves SNR of 91 dB at 200 Hz BW. The sensor shows maximum non-linearity of 0.18 % at the input range of ±1.15 g. The result of the sensor has been presented in the European Solid State Circuits Conference (ESSCIRC) 2012. The paper presenting the further measurement results together with deep theoretical background of the chip has been accepted for the Journal of Solid State Circuits July 2012 issue.
MEMS frequency reference. The design of the interface for the temperature compensation of a MEMS frequency reference also continued in 2011. The research activities in the Circuit Design group within OMFRi project were focused on developing an integrated interface to SETF (Single-Ended Tuning Fork) voltage controlled resonators. Two approaches investigated, resulting in two separate oscillators implemented on the interface ASIC. Each of them features a unique amplitude limiting circuitry. It is critical to keep the drive signal amplitude well controlled to ensure the resonator element operating in the linear regime.

One of the implemented oscillator loops uses continuous level control, Fig. 35. The amplitude of the drive signal is measured and compared to an externally reference value. Based on the outcome of this comparison, the loop gain is regulated with the help of a PI (proportional-integral) controller. This solution is versatile in a sense that the controlled amplitude can be modified during runtime by tweaking the reference voltage of the PI controller. A potential drawback is that the detected amplitude has to be relatively high to ensure accurate operation of the control loop. This requires additional amplification stages which increase overall resource utilization (chip area and current consumption).

![Simplified block diagram of the implemented voltage controlled resonators.](image)
Another approach, requiring less components and able to operate with lower drive signal amplitudes has also been investigated. The structure is a synchronous hard-limiter which simply limits the amplitude instead of continuously controlling its value. It uses a comparator which turns on for the part of the signal period when amplitude is higher than a desired value. The comparator output in turn controls the gain of loop amplifier thus realizing a hard-limiter for the resonator drive signal. This approach allows to implement amplitude limitation with lower amount of resources however may not be as accurate as the continuous control solution.

![Implemented interface ASIC for MEMS oscillators.](image)

**Fig. 36:** Implemented interface ASIC for MEMS oscillators.

Both topologies have been implemented in an interface ASIC (Fig. 36) in AMS 0.35mm high voltage CMOS process. The measurements on the MEMS oscillator prototype, however, showed to be challenging, while the biggest obstacle was the lack of proper model for the MEMS resonator shown in Fig. 37. One step taken to improve the modelling was to initialize the use of Coventor MEMS+ software, which allows moderately precise modelling of the MEMS structures, and straightforward inclusion of the models into circuit simulation tools.

![SEM picture of implemented MEMS fork resonator.](image)

**Fig.37:** SEM picture of implemented MEMS fork resonator.
3.5 Materials and Energy

Universal power management system for energy harvesters. The first design of the power management system was completed. The present system comprises of a charge pump voltage regulator, shown in Fig. 38, used for accurately regulating the output voltage of the system, and a bandgap voltage reference used for providing accurate reference to be used in the regulator. It will be used for verifying the functionality characterizing the performance of the voltage regulator and the novel voltage reference. As shown in Fig. 39, the system will interface different energy harvester types, including photovoltaic, thermal, RF radiation, kinetic and fuel cell harvester, with ultra-low power devices, e.g. sensors, flexible displays, or communication devices providing system start-up, voltage boost and voltage regulation. The system uses supercapacitors for filtering and energy storage. Collaboration with Tampere University of Technology is done for obtaining energy harvesters and supercapacitors, both realized in flexible printed electronics technology. The design has been submitted for manufacturing.

![Block diagram of the charge pump regulator](image1)

**Fig. 38:** The block diagram of the charge pump regulator.

![Block diagram of the system](image2)

**Fig. 39:** The block diagram of the system to be designed. The first design includes the charge pump regulator and the bandgap voltage reference.

Electromagnetic characterization of planar and bulk metamaterials. A strong contribution in this field was done in 2011. First, the previously introduced concept of a so-called Drude-Simovski transition layer which left unexplained the thickness of this layer (the thickness of the transition layer was postulated equal to the lattice period) was replaced by a more advanced concept. This is the concept of excess surface current which compressed the transition layer to an effective
metasurface. Second, the concept of the electromagnetic characterization of real metasurfaces (monolayers of resonant particles) has been developed. The previously known models concerned either non-resonant grids and resulted in first-order modifications of Fresnel formulas or resonant grids without any substrate. The developed theory considers resonant grids on arbitrary substrates. This model allowed us to theoretically reveal an important physical effect we called substrate-induced bianisotropy. This result fits data known from the literature on so-called Plasmon-enhanced solar cells: it gives the only known self-consistent explanation of their anti-reflecting properties. Previous explanations of the Plasmon enhancement replaced a plasmonic grid by a bulk layer of finite thickness. This resulted in an unphysical dispersion of the retrieved permittivity of this effective layer.

**Isotropic negative refraction index from plasmonic nanoparticles.** We have suggested and studied a historically 1st design solution of a metamaterial with the isotropic negative refraction index in the inter-band region (between the visible and near IR ranges). Both effective permittivity and permeability are negative there. It is the lattice of core-shell particle with shell of crystal or amorphous Si and silver core. We have done a detailed study of the optical responses of such inclusions: individual, collective in a planar array, and collective in cubic lattices. We have studied the lattice dispersion for the cases of all possible cubic lattices: simple, body-centered and face-centered ones and finally simulated the negative refraction in 3D arrays of these particles shaped as the wedges (see Fig. 40).

![Image](image_url)

**Fig. 40:** a) – A new constituent of the negative-refraction-index isotropic metamaterial; b) - Spatial distribution of the electric field vector at 360 THz when the Gaussian beam illuminates the wedge structure comprising a simple cubic lattice of such particles. This simulation is the evidence of negative refraction of the beam. The absolute value of the refraction index is less than unity.

**Metamaterial for plasmon-enhanced solar cells.** We have suggested, studied and filed the international patent application of a new material that theoretically allows the significant overall Plasmon enhancement of thin-film solar cells. In all known publications the strong enhancement due to the introduction of the plasmonic nanostructure on top of a solar cell (the best reported result is 43%) is given as a comparison with the solar cell without the nanostructure and without an antireflecting coating (ARC). Calculations show that in these reported cases the introduction of the ARC gives nearly the same effect. The exception is the case when the thickness of the photoabsorbing layer is much smaller than the diffusion length of carriers (e.g. 100-200 nm for Si, CuIn,Ga1-xSe2 (CIGS), or GaAs). Then the ARC does not help, however known plasmonic coverings do not help, too. We understood the reason of this and suggested to implement the
covering as an array of new nanoantennas which possess both substrate-induced bianisotropy and strong quadrupole response. These new coverings were simulated in 2011 for an inter-band solar cell (based on CIGS). Preliminary results were also obtained for a solar cell operating in the visible range (based on silicon). A pre-seed project funded by Aalto Center of Entrepreneurship has been started in 2011 with the purpose of the experimental demonstration of our effect (see Fig. 41).

![Image](image)

**Fig. 40:** (left) – The electric field spatial distribution at 370 THz in the central cross section of the solar cell. The upper layer is the polymer superstrate. The concentration of the field in it does not lead to the energy losses. The intermediate layer is the 100 nm thick p-doped CIGS. The concentration of the field in it leads to the energy conversion. The lower layer is weakly n-doped 300 nm thick CIGS (the bottom electrode below it is not shown); (right) – The same spatial distribution at the upper interface of the photo-absorbing layer. It is clear that the hot spots are concentrated outside the metal elements. This feature results in the strong overall enhancement (29% compared to the solar cell without ARC and 11% compared to the case when ARC is present).

**Metamaterial for prospective thermo-photovoltaic systems.** So-called near-field thermo-photovoltaic systems (NF TPVS) converting the heat into electricity more efficiently than thermoelectric cells operate using the so-called photon tunneling which leads to the dramatic increase of the heat transfer compared to the value restricted by the back-body limit. However, in the mid-infrared range it practically holds only when the gap between two media is as small as a few tens of nanometers. This restriction makes NF TPVS too expensive and not competitive compared to the thermoelectric systems. We have suggested a metamaterial that allows the significant increase of the gap e.g. from 100 nm to 1 µm keeping the same level of the heat transfer.

![Image](image)

**Fig. 42:** (a) and (b) – possible arrangement of nanotubes in the system (d₁ is the 20-50 nm thick free space gap which is small enough to support the photon tunnelling from nanotubes to the cold medium); (c) – the spectrum of the radiative heat transfer across one micron gap. The spectrum is normalized to that carried by propagating waves only (obeying therefore to the black-body limitations). Red curve corresponds to the presence of nanotubes, dashed black curve – to their absence. The one-order gain compared to the black-body transfer in absence of nanotubes corresponds to the photon tunnelling across 1 µm gap.
Our metamaterial does not support neither electron nor phonon heat transfer which could suppress the photovoltaic conversion in the cold medium. The micron gap can be implemented in a relatively inexpensive way with precision 50 nm over the area 1 mm². Such cells can be unified in a large panel. The implementation of our idea can result in a breakthrough in the thermo-photovoltaics, especially if we manage to obtain similar results in the near IR range, where the micron-gap thermo-photovoltaic systems comprising our material will make possible the waste heat conversion with the same overall efficiency as that of near-IR solar cells (i.e. up to 20-25%). Presently, the best micron-gap thermo-photovoltaic systems based on Ge or CdTe demonstrate the efficiency 3% (alone) or 6% (combined with wafer solar cells). The idea and corresponding results are illustrated by Fig. 42.

4. Participation in European projects

Co-ordination:

**TUMESA**

SMARAD (Aalto University Department of Radio Science and Engineering) was the coordinator of project TUMESA (**MEMS Tuneable Metamaterials for Smart Wireless Applications**), which was funded by the European Community within Seventh Framework Programme, Information and Communication Technologies theme. Prof. Antti Räisänen was the Chairman of the Governing Board and Dr. Dmitry Chicherin was the Project Manager until April 2011, and during the remaining time Dr. Juha Ala-Laurinaho was the Project Manager. In addition to Aalto University, the project partners were KTH - Royal Institute of Technology, University of Rennes I, Autocruise S.A. and MicroComp Nordic AB. The objective of the project was to develop components and sub-systems based on microelectromechanical systems (MEMS) in order to provide a cost-efficient and high-performance technology platform for millimetre-wave automotive and industrial radar and future high-capacity communication systems. More precisely, the main goals of the project were: to develop novel on-chip phase shifting and beam-steering devices based on MEMS tuneable high-impedance surfaces; to integrate developed phase shifting components in novel space-efficient antenna arrays on a single chip; to elaborate novel concepts of implementation the beam-steering devices and antenna arrays in cost-efficient radar sensor and future high-capacity wireless communication systems and evaluate fabricated prototypes at a system level. Most of the projects goals were achieved. Duration of the project was 3 years and 4 months, from 1 June 2008 to 30 September 2011. The project website is [http://radio.tkk.fi/tumesa](http://radio.tkk.fi/tumesa).

Participation:

**METACHEM**

From September 2009, SMARAD has been active in the FP7 Research Project METACHEM, Nano-chemistry and self-assembly routes to metamaterials for visible light. Prof. Simovski is responsible for the theoretical part of WP1 of this project and represents the contribution of Aalto into it. WP1 is considered as a step towards a 3D-isotropic metamaterial, operating in the visible range and demonstrating epsilon-near-zero, mu-near-zero, and negative refraction properties without strong spatial dispersion.

**ARTEMOS**

From April 2010, SMARAD has been active in ENIAC research project ARTEMOS (Agile RF Transceivers and Front-Ends for Future Smart Multi-Standard Communications Applications). This project aims at developing architecture and technologies for implementing agile radio frequency
(RF) transceiver capacities in future radio communication products. These new architecture and technologies will be able to manage multi-standard (multi-band, multi-data-rate, and multi-waveform) operation with high modularity, low-power consumption, high reliability, high integration, low costs, low PCB area, and low bill of material (BOM). Prof. Jussi Ryynänen, is responsible of developing direct delta-sigma receiver in WP4 of this project.

**RODIN**

From 2010, SMARAD has been active in the FP7 Research Project RODIN (Suspended Graphene Nanostructures). The RODIN-project is organized around the concept of suspended single-and few-layer graphene nanostructures and annealed diamond-like carbon films. In particular project focuses on engineering and measuring the mechanical and electromechanical properties. Prof. Jussi Ryynänen, is responsible of evaluating electrical performance of developed mechanical resonators.

5. **SMARAD funding**

In **2011 SMARAD funding was as follows:**

<table>
<thead>
<tr>
<th></th>
<th>RAD</th>
<th>SA</th>
<th>MNT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Univ. budget (incl. extra funding for CoE)</td>
<td>1.216.000</td>
<td>404.000</td>
<td>511.000</td>
<td>2.131.000</td>
</tr>
<tr>
<td>External (competitive) funding</td>
<td>1.940.000</td>
<td>965.000</td>
<td>1.613.000</td>
<td>4.518.000</td>
</tr>
<tr>
<td>Total</td>
<td>3.156.000</td>
<td>1.369.000</td>
<td>2.124.000</td>
<td>6.649.000</td>
</tr>
</tbody>
</table>

External funding from the following sources:
- Academy of Finland (CoE) 351.000 136.000 79.000 566.000
- Academy of Finland 519.000 481.000 421.000 1.421.000
- TEKES 418.000 68.000 309.000 795.000
- GETA 83.000 25.000 67.000 175.000
- ESA 40.000 - - - 40.000
- EU 305.000 1.000 98.000 404.000
- Finnish industry and other domestic 224.000 254.000 639.000 1.117.000

6. **SMARAD personnel during year 2011**

In **the Department of Radio Science and Engineering:**

- Ala-Laurinaho, Juha, D.Sc. (Tech.) Senior scientist
- Albooyeh, Mohammad, M.Sc. Doctoral student from February 9th
- Alitalo, Pekka, D.Sc. (Tech.) Post-doctoral researcher
- Amin, Amee, B.Sc. Research assistant from June 1st to August 31st
- Bin Abdullah Al-Hadi, Azremi, M.Sc. Doctoral student
- Chicherin, Dmitry, Lic.Sc. (Tech.) Doctoral student until April 30th
- Dahlberg, Krista, Lic.Sc. (Tech.). Doctoral student
- Du, Zhou, M.Sc. Doctoral student
- Ermolov, Kirill, Mr. Research assistant from June 1st to August 31st
- Generalov, Andrey, M.Sc. Doctoral student
- Geng, Suiyan, Lic.Sc. (Tech.) Doctoral student from September 1st to October 31st
- Haapiainen-Laine, Sari, B.Sc. Project secretary
- Haimakainen, Johannes, Mr. Research assistant from June 1st to October 31st
Haneda, Katsuyuki, D.Sc. | Post-doctoral researcher
Hashemi, Seyedmohamad, M.Sc. | Stipendiate from October 17th
Hernandez Zamora, Bruno, B.Sc. | Erasmus stipendiate from October 17th
Holopainen, Jari, D.Sc. (Tech.) | University teacher
Huang, Yi, B.Sc. | Research assistant from June 1st to August 31st
Icheln, Clemens, D.Sc. (Tech.) | Senior lecturer
Ilvonen, Janne, M.Sc. (Tech.) | Doctoral student
Järveläinen, Jan, M.Sc. (Tech.) | Doctoral student
Kahra, Eino, Mr. | Laboratory technician
Kari, Henri, Mr. | Research assistant from June 1st to August 31st
Karilainen, Antti, M.Sc. (Tech.) | Doctoral student
Karttunen, Aki, Lic.Sc. (Tech.) | Doctoral student
Khanal, Subash, B.Sc. | Research assistant from June 1st
Khatun, Afroza Mst, M.Sc. | Doctoral student
Kivistä, Outi, D.Sc. (Tech.) | Post-doctoral researcher until May 22nd
Kolmonen, Veli-Matti, D.Sc. (Tech.) | Post-doctoral researcher
Kyrö, Mikko, Lic.Sc. (Tech.) | Doctoral student
Laakso, Lauri, Mr. | Laboratory technician
Laitinen Tommi, D.Sc. (Tech.) | Senior scientist
Lindberg, Stina, B.Sc. (Econ.) | HR Secretary
Lioubtchenko, Dmitri, Ph.D. | Academy research fellow
Luukkonen, Olli, D.Sc. (Tech.) | Post-doctoral researcher until May 31st
Majimovitch, Yelena, Dr. | Researcher from June 16th to July 22nd and from November 24th to December 22nd
Mallat, Juha, D.Sc. (Tech.) | Senior university lecturer
Medina Acosto, Gerardo, B.Sc. | Erasmus stipendiate until January 19th
Meriläinen Mikko, Mr. | Research assistant from January 13th to May 31st
Mikhnev, Valeri, Dr. | Senior scientist from June 13th
Morits, Dmitry, M.Sc. | Doctoral student
Mylärä, Tuula, Ms. | Secretary
Mäkelä, Sampo, Mr. | Research assistant from June 1st
Nefedov, Igor, Dr.Sc. | Senior scientist
Niemi, Teemu, B.Sc. (Tech.) | Research assistant
Olkkonen, Martta-Kaisa, M.Sc. (Tech.) | Doctoral student
Parveg, Dristy, M.Sc. | Doctoral student
Planman, Irma, Ms. | HR Secretary
Pousi, Patrik, D.Sc. (Tech.) | Post-doctoral researcher until June 30th
Podlozny, Vladimir, Ph.D. | Project manager and senior scientist
Popovic, Delia, Ms. | Project secretary from August 1st
Poutanen, Juho, M.Sc. (Tech.) | Doctoral student until January 16th
Rasilainen, Kimmo, B.Sc. | Research assistant
Robertson, Jean-Baptiste, M.Sc.Eng | Project coordinator until March 31st
Räisänen, Antti, D.Sc. (Tech.) | Professor, Head of the department
Salo, Sampo | Research assistant from June 1st to August 31st
Schmucki, Lorenz, Mr. | Laboratory technician
Sibakov, Viktor, M.Sc. (Tech.) | Laboratory manager
Simovski, Constantin, Dr.Sc. | Visiting professor
Song, Jinsong, B.Sc. | Research assistant from January 24th
Tamminen, Aleksi, Lic.Sc. (Tech.) | Doctoral student
Takizawa, Kenichi, Dr. Visiting researcher from August 17th
Tretyakov, Sergei, Dr.Sc. Professor
Vahdati, Ali, M.Sc. (Tech.) Doctoral student from January 26th to July 31st
Valkonen, Risto, M.Sc. (Tech.) Doctoral student
Vainikainen, Pertti, D.Sc. (Tech.) Professor
Vehmas, Joni, B.Sc. (Tech.) Research assistant
Virk, Usman, B.Sc. Research assistant from February 1st
Zvolensky, Tomas, M.Sc. Doctoral student

In the Department of Signal Processing and Acoustics:
Aho, Janne, B.Sc. (Tech.) Research assistant from August 3rd
Aittomäki, Tuomas, M.Sc. (Tech.) Doctoral student
Balakrishnan, Arun, Mr. Stipendiate until August 31st
Bica, Marian, B.Sc. Research assistant
Bysany D., Satish, B.Sc. Research assistant from March 21st
Chaudhari, Sachin, M.Sc. Doctoral student
Cierny, Michal, M.Sc. Doctoral student
Dhamala, Ujjwal, B.Sc. Research assistant
Eriksson, Jan, D.Sc. (Tech.) Senior scientist
Haghparast, Azadeh, M.Sc. Doctoral student until July 27th
Hynninen, Jussi, M.Sc. (Tech.) Computer administrator
Jacob Mathecken, Pramod, M.Sc. Doctoral student
Jänis, Pekka, M.Sc. (Tech.) Doctoral student
Kashyap, Neelabh, B.Sc. Research assistant from January 12th
Koivisto, Tommi, M.Sc. (Tech.) Doctoral student
Koivunen, Visa, D.Sc. (Tech.) Academy professor
Le, Vieth-Anh, M.Sc. Doctoral student from October 10th
Lemetyinen, Mirja, Ms. HR secretary
Lundén, Jarmo, D.Sc. (Tech.) Post-doctoral researcher
Oborina, Alexandra, M.Sc. Doctoral student
Ojaniemi, Jaakko, M.Sc. Doctoral student from December 5th
Oksanen, Jan, M.Sc. Doctoral student
Ollila, Esa, D.Sc. (Tech.) Academy research fellow
Pereira Da Costa, Mario, M.Sc. Doctoral student
Pölönen, Keijo, M.Sc. (Tech.) Doctoral student
Rajasekharan, Jayaprakash, M.Sc. Doctoral student
Razavi, Seyed Alireza, D.Sc. (Tech.) Post-doctoral researcher from September 1st
Riihonen, Taneli, M.Sc. (Tech.) Doctoral student
Richter, Andreas, D.Sc. Professor
Saeed, Umar, B.Sc. Research assistant
Salmi, Jussi, D.Sc. (Tech.) Post-doctoral researcher
Schöber, Karol, M.Sc. Doctoral student
Sikander, Ulla, Ms. Project secretary
Simonen, Tarmo, M.Sc. (Tech.) Computer administrator
Werner, Stefan, D.Sc. (Tech.) Academy research fellow
Wichman, Risto, D.Sc. (Tech.) Professor

In the Department of Micro and Nanosciences:
Aaltonen, Lasse, Lic.Sc. (Tech.) Doctoral student
Gronicz Jakub, M.Sc. (Eng.) Doctoral student
7. Visitors to SMARAD in 2011

Visiting Professors:
- Ass. Prof. Takahiro Aoyagi, Tokyo Institute of Technology, Japan, 1 week
- Prof. Olga Glukhova, Saratov State University, Russia, 2 weeks
- Prof. Gregorio Fernando, Universidad Nacional del Sur, Argentina, 2 weeks
- Prof. Marcello de Campos, Universidad Federal do Rio de Janeiro, Brazil, 1 week
- Prof. Sergiy Vorobyov, University of Alberta, Kanada, 1 week
- Prof. Sumit Roy, University of Washington, USA, 1 week
- Prof. Vincent H. Poor, Princeton University, USA, 1 week

Visiting Researchers:
- B.Sc. Bruno Hernandez Zamora, Universidad Autonoma de Madrid, Spain, 4 months
- B.Eng. Soichi Saito, Tokyo Denki University, Japan, 2 months
- M.Eng. Daisuke Sugizaki, Tokyo Denki University, Japan, 1 month
- B.Eng. Kenshiro Tsutsuki, Tokyo Denki University, Japan, 1 month
- M.Sc. Seyedmohammad Hashemi, Iran University of Science and Technology, Iran, 3 months
- Dr Constantinos Valagiannopoulos, University of Athens, Greece, 12 months
- M.Sc. Amin Enayati, IMEC, Katholieke Universiteit Leuven, Belgium, 7 months
- Dr Yelena Maksimovich, Institute of Applied Physics, Minsk, Belorussia, 2 months
- Dr Kenichi Takizawa, National Institute of Information and Communications Technology, Japan, 5 months
- M.Sc. Inigo Liberal, Public University of Navarra, 4 months

8. Visits from SMARAD to foreign institutes in 2011

- Dr Pekka Alitalo, German Aerospace Center, Wessling, Germany, 2 months
- Dr Katsuyuki Haneda, University of Southern California, Los Angeles, USA, 2 weeks
- Dr Katsuyuki Haneda, Tokyo Denki University, Japan, 2 weeks
– Prof. Constantin Simovski, ITMO, St. Petersburg, 2 weeks
– M.Sc. Tomas Zvolensky, Queen's University, Belfast, UK, 1 month
– Dr Marko Kosunen, University of California, Berkeley, USA 3 months
– Dr Mikko Varonen, JPL California Institute of Technology, USA, 11 months
– Academy prof. Visa Koivunen, Princeton University, USA, 2 months
– Dr Jarmo Lunden, Princeton University, USA, 8 months
– M.Sc. (Tech.) Jan Oksanen, Princeton University, USA, 2 months
– Dr Esa Ollila, Princeton University, USA, 8 months
– Dr Jussi Salmi, University of Southern California, USA, 1 month

9. Post-graduate degrees

Doctor of Science (Technology) degrees in 2011:

Jari Holopainen
Compact UHF-band antennas for mobile terminals: focus on modelling, implementation, and user interaction
Thesis defence: 29 April 2011
Opponents: Prof. Dirk Manteuffel, Christian-Albrechts-Universität, Kiel, Germany, and Dr Kevin Boyle, EPCOS, UK Ltd, U.K.
Preliminary examiners: Prof. Ph.D. Koichi Ito, Chiba University, Japan, and Dr Ping Hui, Nokia Corporation, Canada
Supervisor: Prof. Pertti Vainikainen

Ville Saari
Continuous-time low-pass filters for integrated wideband radio receivers
Thesis defence: 29 April 2011
Opponent: Prof. Mohammed Ismail, The Ohio State University, USA
Preliminary examiners: Assoc. Prof. Andrea Baschirotto, University of Milano-Bicocca, Italy, and Dr Kimmo Koli, ST-Ericsson, Finland
Supervisor: Prof. Jussi Ryynänen

Juho Poutanen
Geometry-based radio channel modelling: Propagation analysis and concept development
Thesis defence: 13 May 2011
Opponents: Dr Jonas Medbo, Ericsson Research, Sweden, and Prof. Martine Lienard, University of Lille, France
Preliminary examiners: Prof. Mir Ghorashi, Tokyo Institute of Technology, Japan, and Dr Tricia Willink, Communication Research Centre, Canada
Supervisor: Prof. Pertti Vainikainen

Suiyan Geng
Millimeter wave and UWB propagation for high throughput indoor communications
Thesis defence: 2 November 2011
Opponent: Fredrik Tufvesson, Lund University, Sweden
Preliminary examiners: Dr Chia-Chin Chong, NTT Dokomo Labs, Palo Alto, USA, and Prof. Hirokazu Sawada, Tohoku University, Sendai, Japan
Supervisor: Prof. Pertti Vainikainen

Tero Kiuru
Characterization, modelling, and design for applications of waveguide impedance tuners and Schottky diodes at millimeter wave lengths
Thesis defence: 12 December 2011
Opponent: Prof. Jan Stake, Chalmers University of Technology, Gothenburg, Sweden
Preliminary examiners: Dr Thomas Crowe, Virginia Diodes Inc., Charlottesville, USA, and Dr Imran Mehdi, Jet Propulsion Laboratory, Pasadena, USA

Supervisor: Prof. Antti Räisänen

Dmitri Chicherin
Studies on microelectromechanically tuneable high-impedance surface for millimetre wave beam steering
Thesis defence: 2 December 2011
Opponent: Prof. Didier Lippens, Université des Sciences et Technologie de Lille, France
Preliminary examiners: Prof. Wolfgang Menzel, University of Ulm, Germany, and Dr Tauno Vähä-Heikkilä, VTT Technical Research Centre of Finland
Supervisor: Prof. Antti Räisänen

Licentiate of Science (Technology) degrees in 2011:

Krista Dahlberg
Mixer test jig for millimeter wave Schottky diodes (Testialusta milimetraaaltoalueen Schottky-diodeille)
Graduation date: 7 February 2011
Supervisor: Prof. Antti Räisänen
External examiner: Dr. Jyrki Louhi, Nokia Siemens Networks

Aleksi Tamminen
On developments in submillimeter-wavelength imaging (Alimillimetraaaltoalueen kuvantamismenetelmien kehittämisestä)
Graduation date: 6 October 2011
Supervisor: Prof. Antti Räisänen
External examiner: Dr Ville Viikari, VTT Technical Research Centre of Finland

10. Publications

10.1 Articles in scientific journals with peer-review


### 10.2 Articles in conference proceedings and in other edited works


47


Espoo, Finland, Aalto University, School of Science, Dept. of Applied Physics, August 22-26, 2011, p. 29.


10.3 Published monographs

No monographs published in 2011

10.4 Other scientific publications


10.5 Text books and other books related to scientific research


10.6 Chapters in books


11. Other scientific activities of SMARAD members

University Boards:

**Kari Halonen**
- Member, Steering group of Aalto School of Electrical Engineering
- Member, Doctoral Programme Committee of Aalto School of Electrical Engineering
- Member, Board of Directors of MilliLab
- Department Head, Department of Micro and Nanosciences

**Visa Koivunen**
- Vice-leader, SMARAD CoE

**Jussi Ryynänen**
- Head of Electronics and Electrical Engineering (EST) study programme
- Vice Chair, EST degree programme committee
- Member, Aalto Bachelor study renewal committee

**Antti Räisänen**
- Chairman, Doctoral Programme Committee of Aalto School of Electrical Engineering
- Member, Steering group of Doctoral Education of Aalto University
- Member, Steering group of Aalto School of Electrical Engineering
- Department head, Department of Radio Science and Engineering
- Leader, SMARAD CoE
- Chairman, Board of Directors of MilliLab

Participation in Organization of Scientific Conferences and Membership in Expert Boards

**Kari Halonen**
- TPC Member, European Solid-State Circuits Conference
- TPC Member, IEEE International Solid-State Circuits Conference
- TPC Chair and member of Organizing Committee of ESSCIRC 2011 Conference in Helsinki
- Member, Management Group of NORCHIP Conference
- Member, Management Group of PRIME workshop
- Associate Editor, IEEE Journal of Solid-State Circuits
- Member, Editorial board of Springer International J. of Analog Integrated Circuits and Signal Processing

**Visa Koivunen**
- Fellow, IEEE
- Associate Editor, Signal Processing
- Associate Editor, IEEE Transactions on Signal Processing
- Associate Editor, EURASIP Journal of Wireless Communications and Networking
- IEEE Signal Processing Society, Industrial Liaison board
- Member and industry liaison, IEEE Signal Processing for Communications Technical Committee (SPCOM-TC)
- Member, IEEE Sensor Array and Multichannel Signal Processing Technical Committee (SAM-TC)
– KTH advisory board, ICT area
– COST IC902 Cognitive Radios, Finland representative

**Jussi Ryynänen**
– TPC Member, European Solid-State Circuits Conference ESSCIRC 2011
– TPC Member, European Conference on Circuit Theory and Design, ECCTD 2011
– Workshop chair ESSCIRC 2011

**Antti Räisänen**
– Fellow, IEEE
– Edmond S. Gillespie Fellow, AMTA
– Member of the Board of Directors, Member of the General Assembly, European Microwave Association (EuMA)
– Chairman of the EuMA Awards Committee
– Member, Steering Committee of the European School of Antennas
– Member, Steering Committee, ESF NEWFOCUS
– Member of the TPC, 5th European Conference on Antennas and Propagation, EuCAP2011 (Rome, Italy, 11-15 April, 2011)
– Co-Chair of the Steering Committee, 4th Global Symposium on Millimeter Waves, GSMM2011 (Espoo, Finland, May 23–25, 2011)
– Member of the TPC, 14th European Microwave Week, EuMW2011 (Manchester, UK, 9-14 October, 2011)
– Member of the TPC, 6th ESA Workshop Workshop on Millimetre-Wave Technology and Applications (Espoo, Finland, May 23-25, 2011)
– Member of the TPC, 33rd Annual Antenna Measurement Techniques Association (AMTA) Symposium (Denver, USA, 16-21 October, 2011)

**Sergei Tretyakov**
– Fellow, IEEE
– Fellow, Electromagnetics Academy
– President, the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials
– Member, Steering Committee of the European Doctoral Programme on Metamaterials
– Deputy member, URSI Finnish National Committee
– General chair, 5th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (Barcelona, Spain, October 2011)
– Member of the TPC, Optics & Optoelectronics Congress on 18-22 April 2011 in Prague
– Member of the TPC, SPIE Optics + Photonics, Metamaterials: Fundamentals and Applications IV, 21-25 August 2011, San Diego, California, USA
– Member of the TPC, 2011 International Conference on Problems of Interaction of Radiation with Matter, October 26-28, 2011, Gomel, Belarus
– Member of the TPC, Loughborough Conference on Antennas and Propagation, 14-15 Nov. 2011, UK
– Member, Expert Advisory Group for Nanosciences, Nanotechnologies, Materials and New Production Technologies (European Commission, 7th Framework Programme)

**Risto Wichman**
– Official Member, URSI Finnish National Committee, Radiocommunication Systems and Signal Processing
– Local liaison office, EURASIP
– TPC Member IEEE Globecom
– Steering Group Member, COST IC0803 RF/Microwave Communication Subsystems for Emerging Wireless Technologies

Review Activities

Kari Halonen

Visa Koivunen
– Reviews for conferences IEEE ICASSP, IEEE SPAWC, IEEE SAM, IEEE PIMRC, IEE ICC

Jussi Rynänen
– Review for research proposal, NWO, The Netherlands Organisation for Scientific Research

Antti Räisänen
– Editorial Board Member, Experimental Astronomy
– Evaluation for ERC
– Evaluations for IEEE Fellow Committee, USA
– Evaluations for ESF Research Networking Programme
– Evaluation for Agence Nationale de la Recherche, France
– Evaluation for a faculty position in Information and Communication Technology: Chalmers University of Technology, Sweden
Constantin Simovski

Sergei Tretyakov
– Editorial Board Member, Progress in Electromagnetics Research, Problems of Physics, Mathematics, and Technics

Pertti Vainikainen

Risto Wichman
– Evaluation of project proposals for Czech Science Foundation and Austrian Science Foundation