INSTITUTE OF TELECOMMUNICATIONS
VIENNA UNIVERSITY OF TECHNOLOGY

RESEARCH ACTIVITIES

2009 – 2013

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

institute of telecommunications

Preface

This report is to give an overview over the recent activities in teaching and research at the *Institute of Telecommunications* at Vienna University of Technology. The reporting period 2009—2013 was one of profound changes: after I became head of institute in 2010, we implemented the merger with the former Institute of Broadband Communications – because of the merger, the institute was given its new name and a new logo –, we realized complete refurbishments of the workshop and the 6th floor as well as various organizational changes and a restructuring of the bachelor and master programs.

The research groups at the institute, each headed by a professor, are specialized in a broad range of topics including Mobile Communications, Flexible Wireless Systems, Multimedia Systems, Communication Networks, Signal Processing, Communication Theory, Robust Communications and Radio-Frequency Engineering, as well as Broadband and Optical Communications. Work items at the institute range from fundamental and theoretical topics to applied research with strong connections to telecommunications industry – further details are provided by this report. We are very delighted that Tanja Zseby accepted (in 2013) the position as a full professor of Communication Networks, as a successor of Prof. Harmen van As. Her research in the rather important field of network security, with a focus on smart grids, and the new lab on the 6th floor will considerably strengthen our research portfolio.

During the reporting period the institute had to cope with very significant changes in teaching, which included a makeover of the department's Bachelor program in Electrical Engineering and Information Technology as well as a complete re-design of the master program in Telecommunications. The institute is now responsible for four compulsory lecture courses (each with more than 200 students) in the bachelor program. The new master program in Telecommunications has six strands, with one path at the core of Telecommunications research being fully delivered in English and, hence, also allowing international students to study at our institute and qualify for our PhD program. The other five strands connect to the other master programs of the department, which allows students for high flexibility in picking their areas of interest.

Apart from the professors, the institute has in excess of 60 research staff, including senior academics, post docs and PhD students; the vast majority is sponsored by external funding. Support by industry and funding bodies is crucial not only for the research agendas of the institute: teaching also benefits very significantly, because students working on their master and bachelor theses are heavily involved in funded projects, in which they get hands-on experience and contacts to future employers.

In the reporting period we note the retirement (Emeritierung) of Prof. Harmen van As who (until the merger of the institutes) had been the head of the Institute of Broadband Communications. He has, for many years, been a major international figure in his field and, fortunately, he remains an active member of the new institute, similar to his retired colleagues Prof. Leeb, Prof. Weinrichter, Prof. W. Mecklenbräuker and Prof. Bonek, who are all seen regularly at the institute: we are very grateful to all of them for their continued support!

Any institute, a large one as ours in particular, would not work without support by secretaries, technicians and accountants. Common to all support services is that they are only noticed when they are not there – an experience that, fortunately, we hardly ever make. On behalf of the institute I would like to express my sincere gratitude for this!

I would like to thank all our supporters, particularly those from industry, for their continued engagement to fund research at our institute. Thanks go to the funding bodies, in particular the Austrian Science Fund (FWF), the Vienna Science and Technology Fund (WWTF), the European Research Council (ERC) and the Christian Doppler Gesellschaft (CDG): our research would not be possible without their support.

Finally, I would like to thank all colleagues, students and supporters for their personal commitment to make the institute the excellent and likable place it is.

Vienna, December 2013

Norbert Goertz
Head of Institute

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Contents

Impressum

Erscheinungsjahr 2014
Eigentümer, Herausgeber und Verleger:
Institute of Telecommunications
Technische Universität Wien
Gußhausstraße 25/389, A-1040 Wien

http://www.nt.tuwien.ac.at

Für den Inhalt verantwortlich: Prof. Dr. Markus Rupp
Sekretariat: Andrea Engelmaier
Umschlagfoto: Dipl. Ing. Johannes Gonter
Gestaltung und Satz: Ing. Bernhard Wistawel
Druck: Ferdinand Berger & Söhne GmbH, 3580 Horn

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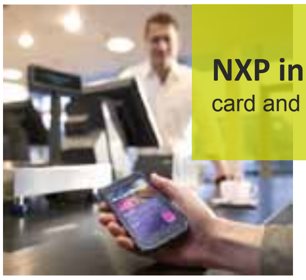

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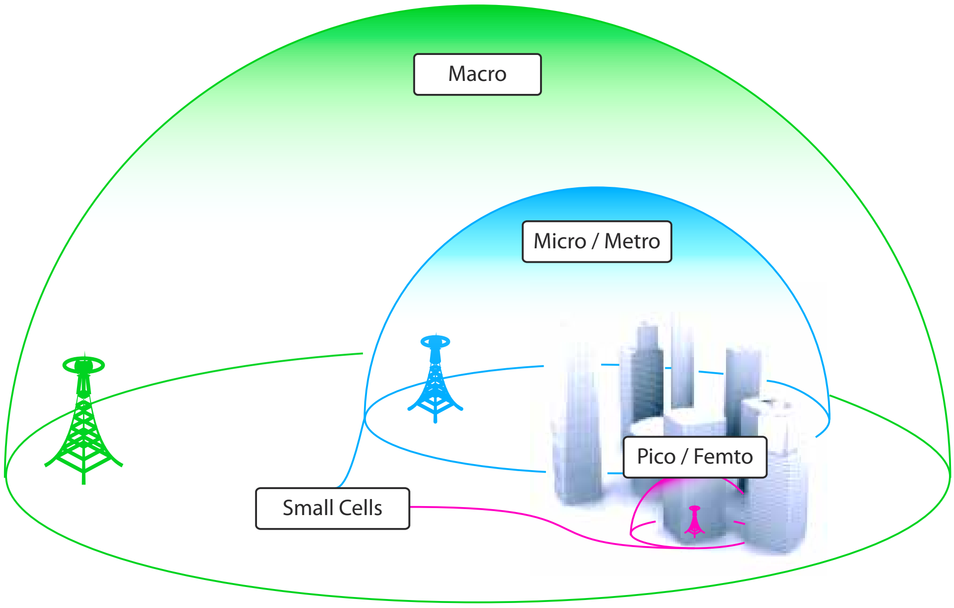
Mobile Radio

Heterogeneous Networks

Due to the literal explosion of mobile data traffic, we are currently facing a transition from the era of coverage to the era of capacity. However, the increasing load can hardly be carried by existing macrocellular networks. A key factor to sustain the higher demand is the efficient spatial reuse of available frequency resources. This goes hand in hand with shrinking cell size and the idea to bring the base station closer to the user. New base station classes with low power and small coverage area (micro, pico, femto), which are typically employed within the coverage area of the macrocell, form the basis for novel network topologies, denoted as heterogeneous cellular networks. The "mobile communications group" at the ITC currently investigates on the optimal deployment of small cells at places with particular high traffic, such as shopping malls, office buildings and public spaces.
Small cells are considered as one of the most promising tools to cope with the exponentially increasing demand on cellular network capacity, by placing autonomous access



points (micro, pico or femto base stations) at user hot spot locations, to offload traffic from the macro cellular network. This approach is especially suitable for situations in which the small cells are well isolated from the macro network (e.g., through walls of a building), such that the access points do not cause excessive interference to the macro base stations. If such isolation is not in place, coordination of several layers of the network is required to handle the interference between base stations and access points, which is known as coordinated transmission. In the "mobile communications group" at the ITC, novel coordination techniques are devised to improve the efficiency and capacity of future cellular networks. Their feasibility and potential is evaluated employing sophisticated LTE network simulators that have been developed and implemented within the research group.

Coordinated Multipoint

Machine to Machine Communication

Machine to machine (M2M) communication services allow systems to communicate with devices of the same ability. In M2M communications, devices capture events, e.g., environmental measurements such as temperature and forward them through the network towards a central server. This scenario is expected to scale with the number of smart devices to levels far beyond the human users in a network. In a mobile cellular network, the traffic impact will be huge as these networks are optimized for throughput rather than number of parallel users. In the research group we are working on different approaches to enable such traffic in nowadays networks. Currently we are working on novel detection algorithms for M2M devices as a first step. In parallel new traffic, models are derived from the systems under test. These models are also enhanced with a spatial distribution of the nodes. This new element allows future research of new scenarios based on spatial events such as earthquakes.

LTE-A Testbed

The MIMO testbed developed at our institute is capable of testing and investigating new techniques and algorithms for mobile communications in a real world scenario in such a flexible way that typically only simulations provide. Therefore, the time consuming task of implementing algorithms on hardware is not required. The transmit signals are computed in software, are then transmitted in real time over real-world channels before the evaluation of the received signals is performed offline after the measurement. To this end up to three identically transmitters at different locations with four antennas each and one receiver with four antennas can be employed. In addition to measurements with recent standards such LTE and LTE-A, the testbed is used to test and evaluate new ideas for the future generations of mobile communications.

Univ.Prof. Dipl.-Ing. Dr.techn. Markus Rupp

Communication Networks

Network Security

The protection of communication networks against new and unexpected attacks remains a challenging task. New vulnerabilities emerge every day and attacks become more sophisticated. Proactive solutions often fail if new attack strategies are used or undetected vulnerabilities are exploited. Therefore, network supervision methods are essential to establish situational awareness in communication networks. They help to detect anomalies in communication patterns and provide the first step for the detection of new attack types.

The communication networks group works on network supervision and network protection methods, anomaly detection techniques and mitigation strategies.

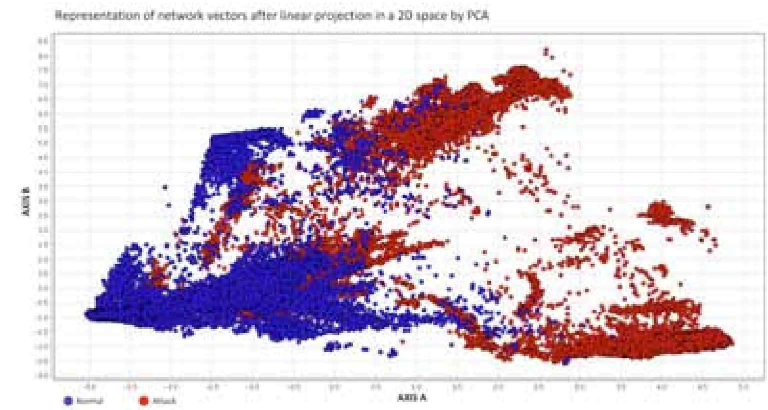


Figure 1: Detection of Anomalies in Communication Networks: Projection of multidimensional feature vectors to 2-dimensional space

Secure Communication in Cyber-Physical Systems

Cyber–physical systems (CPS) interconnect real world physical systems with computational components in cyberspace. Cyber–physical systems provide the basis for many critical infrastructures (such as smart power grids) and are therefore tempting targets for all kinds of attackers. As a consequence, communication networks for cyber–physical systems have high security demands. Interfering with supervision and control functions in cyberspace can influence real world physical systems, which can lead to the damage of physical devices, malfunction of critical processes and endangerment of human lives.

The Communication Networks group works on methods to protect and supervise communication networks for Cyber-Physical Systems. The group focuses on communication solutions for smart grid environments, including Advanced Metering Infrastructures (AMIs) and Wide Area Monitoring Systems (WAMS). As part of this, the group works on secure machine-to-machine communication in different network settings with emphasis of communication protocols based on IPv4 and IPv6.

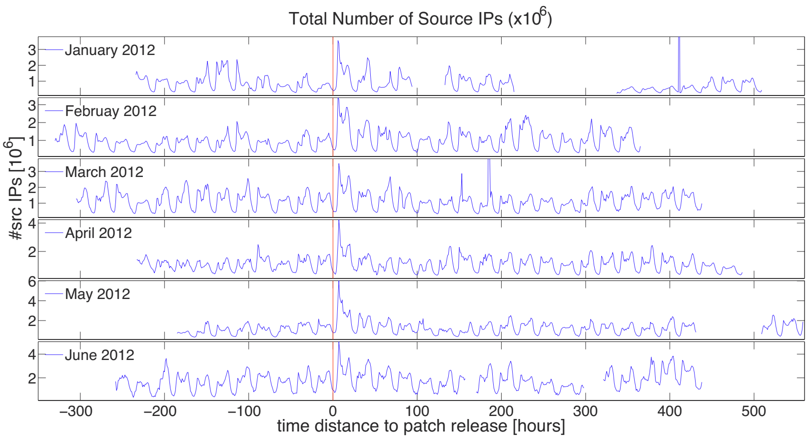


Figure 2: "Exploit Wednesday" Effect: Increase of number of sources scanning for new vulnerabilities each month at midnight after patches have been released on Patch Tuesday

Univ.Prof. Dipl.-Ing. Dr.-Ing. Tanja Zseby

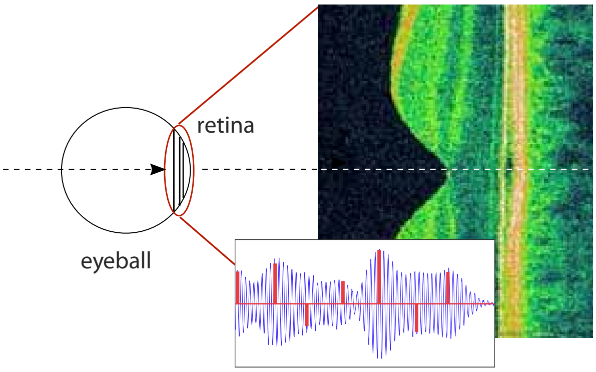
Signal Processing

Major directions and applications of our recent signal processing research include statistical signal processing, sensor networks, and wireless communications. Our research has been supported by the Austrian Science Fund (FWF) under grant "Statistical Inference" within the National Research Network SISE ("Signal and Information Processing in Science and Engineering"), by the Vienna Science and Technology Fund (WWTF) under grants SPORTS ("Sparse Signals and Operators: Theory, Methods, and Applications") and NOWIRE ("Noncoherent Wireless Communications over Doubly Selective Channels"), and by the European Union within the FP6/FP7 project NEWCOM ("Network of Excellence in Wireless Communications").

Statistical Signal Processing

Our focus in the area of statistical signal processing has been on methods that exploit sparsity. We developed Monte-Carlo methods for blind sparsity-exploiting detection and estimation. These methods combine a block or partially collapsed Gibbs sampler with a sparsity constraint, e.g., in the form of a lower bound on the temporal or spatial minimum distance of two consecutive signal components. We applied our methods to deconvolution, signal analysis in optical coherence tomography, wave detection, delineation, and estimation in electrocardiography, and multipath component estimation.

We also proposed compressive spectral estimators for "time-frequency sparse" nonstationary random processes. These estimators extend a standard spectral estimator for nonstationary random processes by a compressed sensing technique that allows for a reduction of the number of measurements.

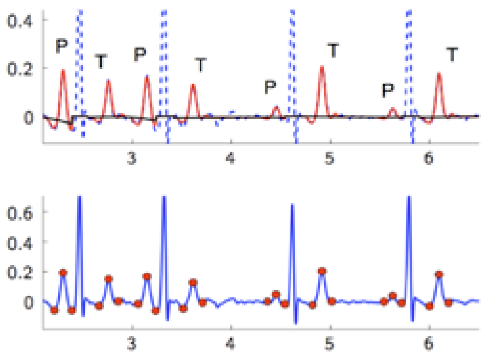


Two-dimensional scan of the retina and one-dimensional reflectivity function (red bars) estimated by means of a Bayesian detection/estimation method (Courtesy of B. Hofer and W. Drexler, Medical University of Vienna).

More on the theoretical side, we investigated minimum variance estimation of sparse vectors using the mathematical theory of reproducing kernel Hilbert spaces. Here, our focus was on closed-form characterizations of the locally minimum variance estimator and its performance. We also derived performance bounds for sparse parametric covariance estimation.

We derived an iterative inference (message passing) algorithm that combines "belief propagation" message passing with "mean field approximation" based message passing, which are applied to disjoint parts of an underlying factor graph. The combined algorithm was successfully applied to joint data decoding and channel estimation.

Finally, we developed a low-complexity approximation of the "belief propagation" message passing algorithm based on the unscented transformation. This algorithm extends the unscented Kalman filter to general factor graphs and enables an efficient approximate marginalization of distributions with a general factor structure.



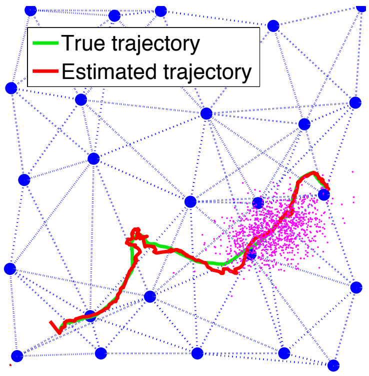
Detection/estimation of the P and T waves in an ECG signal.

Sensor Networks

In the area of statistical signal processing for wireless sensor networks, we pursue a fully distributed (decentralized, cooperative) approach that does not require a central processing unit. Our goal has been to estimate global or local states using only local processing at the individual sensor nodes and communication between neighboring sensor nodes. An example is the task of estimating the locations and velocities of moving objects, using spatially distributed sensors that sense acoustic or radio signals emitted by these objects.

For distributed sequential estimation in wireless sensor networks, we developed distributed particle filters that use consensus algorithms to disseminate relevant statistical information across the sensor network. In particular, we proposed the likelihood consensus scheme for a distributed calculation of the global likelihood function. The resulting distributed particle filters outperform state-of-the-art methods while requiring less intersensor communication.

We also devised distributed estimation methods based on factor graphs and the belief propagation algorithm. An important aspect of these methods is the reduction of intersensor communication by using parsimonious parametric representations of probability distributions. We were able to accommodate noncooperative network nodes (e.g., moving objects not communicating with the sensor nodes) by combining belief propagation with the likelihood consensus scheme. Using this approach, we devised distributed algorithms for cooperative simultaneous localization and tracking and for cooperative simultaneous localization and synchronization.

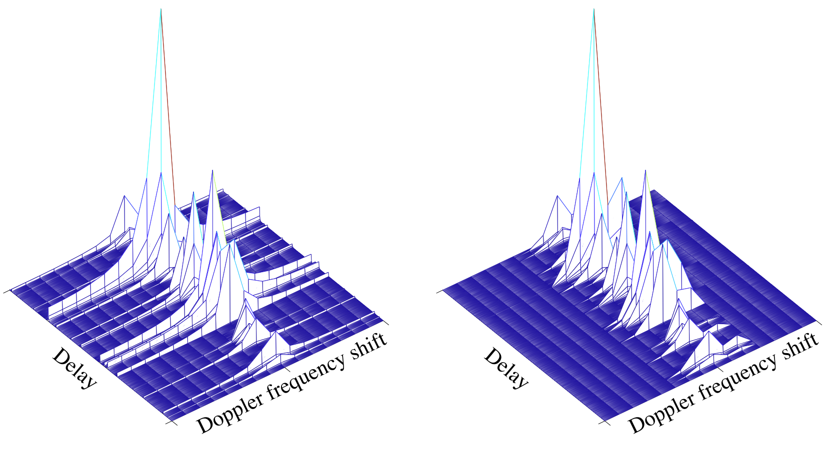


Distributed tracking of a moving object in a sensor network.

Wireless Communications

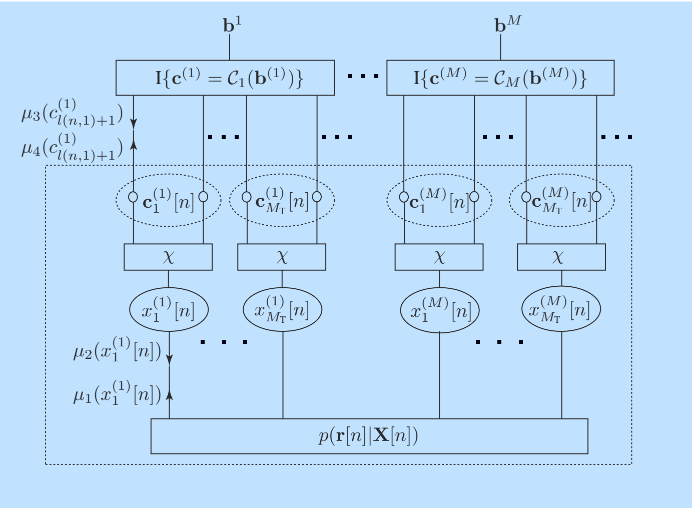
Our recent contributions to the area of wireless communications include receiver algorithms for communication over doubly selective and frequency-selective channels and information-theoretic performance bounds for noncoherent communications.

For multicarrier (OFDM) transmissions over doubly selective channels, we proposed compressive channel estimators that exploit the channels' sparsity in the delay-Doppler domain to achieve a reduction of pilot overhead. We devised extensions of these estimators to group sparsity, multiple-antenna (MIMO) channels, and sequential operation. Furthermore, we proposed a low-complexity intercarrier/intersymbol interference equalizer. This method combines a decision-feedback stage with an extension of the iterative LSQR algorithm that uses groupwise interference cancelation with reliability-based sorting of sets of subcarriers. We also considered the design of transmit/receive pulses for optimum equalization performance.



Delay-Doppler representation of a double selective communication channel, using a standard Fourier basis (left) and an optimized basis yielding improved sparsity (right).

For multiuser communication systems employing multiple-antenna multicarrier (MIMO-OFDM) transmission and interleave division multiple access (IDMA), we devised iterative receivers based on factor graphs and the belief propagation algorithm. IDMA is a recently proposed multi-access technique that provides an attractive alternative to code division multiple access (CDMA). Our receivers combine demodulation, decoding, and channel estimation in an iterative "turbo-style" architecture. The consistent integration of channel estimation in the iteration loop was observed to yield substantial performance gains.



Factor graph (detail) of an iterative MIMO-IDMA receiver.

For large MIMO systems, we proposed low-complexity data detectors with a novel three-stage architecture that combines partial maximum-likelihood detection, soft-value generation, and high-dimensional optimization. These detectors can outperform state-of-the-art methods based on nulling and canceling, semidefinite relaxation, or likelihood ascent search.

Finally, we investigated the degrees of freedom (capacity pre-log) of nonconstant block-fading MIMO channels in the noncoherent setting. We showed that the number of degrees of freedom can be significantly larger than for the widely used constant block-fading MIMO model.

Ao.Univ.Prof. Dipl.-Ing. Dr.techn. Franz Hlawatsch

Robust and Reliable Communication

The globalization demands a rapid boost on mobile communications. The limited bandwidth in turn has forced the telecommunication standards to open the stringent regulations. The consequence for a communication system is that it is not (precisely) predictable in advance with which type of interference the system is confronted with. In the past the communication engineers have put much effort to predict the interference (the channel state) as accurate as possible. The problems with prediction are well known (error in the estimate, time consuming, power consuming, complex algorithms, stability problems). If you know exact and in advance the channel state you can design the detection process accurately and you will reach an optimum solution for a predefined quality measure. In the future it will be much more complicated to continue this design philosophy because the interference will become more severe (the type of the interference will range in a wide span, the dynamic of the interference will be fast, the type of errors will range between single error events to burst error structure). Sources of interference range from permanent or pulsed AWGN to multipath interference for the single-user case and extend to multi-user interference, multi-cell interference, man-made noise to heavily electromagnetic polluted industrial environments. The quality of service range from simple voice communication to secure data-communication.

The goal of this investigation is to find a unique solution for all possible future challenges. This can be achieved if we accept some small degradation in the quality of service. This leads to the concept of robust and reliable communications in which the degradation of some predefined optimum quality measure is allowed. This means that the optimum point in a parameter space spreads out to form an acceptance-volume. This drift from the optimum solution to a suitable solution (sub-optimum) opens the opportunity to design communication systems that have low power consumption, low complexity, a high degree of flexibility, highly availability and cheap. One aspect which will be more present in the future is intentional jamming. The movement from a commercial application to a military environment is apparent under the light of globalization and the tendency to open of the telecom market and a dramatic increase of users make the environment more hostile.

The point is that we have to change a complex design with a simple design with integrated interference reduction capabilities. Such a design philosophy is better prepared for future wireless challenges (we do not know now) if we can't predict the interference environment in advance.

The solution proposed in this project is in focusing on simple interference reduction algorithms which make no (less) assumptions about the interference type, composition and offers a great improvement in performance. The best suited tool for this task is to use adaptive nonlinearities driven by threshold crossing information which is simple and fast and derived online. This solution method fits to the assumptions made above. The first result for robust and reliable communication systems for a very specific application (simple design of a digital correlation receiver) was very promising.

Possible applications for the proposed robust and reliable communication schemes range from terrestrial mobile voice- and data communication, telemetry in heavy electromagnetic polluted industrial production halls (data communications from a rotating machine to a nearby receiver), assembly lines, health-care and to applications which are not known today.

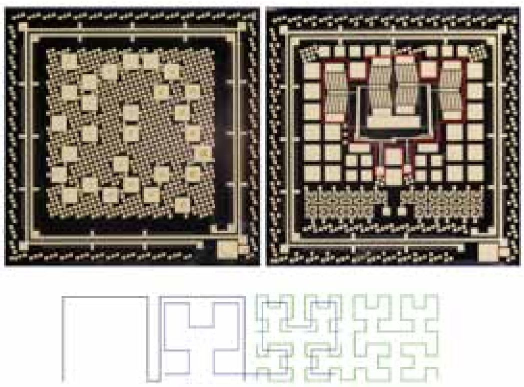
Ao.Univ.Prof. Dipl.-Ing. Dr.techn. Alois Goiser

Flexible Wireless Systems

Present 3G wireless systems enable efficient transmission and distribution of digital content: The Internet has arrived in the mobile domain and allows the generation, transmission, distribution, storage, and manipulation of information. The next technical challenge is the extension of the mobile Internet to production, transportation, distribution, storage, and manipulation of objects ("internet of things"). Wireless technologies need to become dependable. This requires major improvements in availability (coverage) and transmission latency, packet delivery guarantees, guaranteed data rates, as well as energy efficiency and cost structure. Therefore, we investigate novel transmission techniques and protocols, their behavior at high network load energy efficient solutions.

The use of MIMO transmission using antenna array technology has become the commercially available state of the art since 3.5G mobile communications. The current trend towards MIMO-OFDM continues. Major improvements compared to UMTS since 2006 have been achieved in spectral efficiency from the use of dynamic resource allocation which takes into account the current system load, advanced precoding techniques, and spatial multiplexing.

Direct radio communication between mobile entities enjoys a renaissance in connection with the recent interest in peer-to-peer and ad-hoc networks. This is especially true for safety-related vehicle-to-vehicle communication to enable advanced active safety. Traffic telematics applications are currently under intense research and development for making transportation safer, more efficient, and cleaner. Co-operative systems have become an important field of research in the area of telematics. Wireless networking of sensors and instrumentation enables new application fields: Intelligent Transport, Smart Metering, Intelligent Production, etc. We investigate dynamic resource allocation schemes which employ channel prediction, take into account the current system load, as well as transmission latency. Here, we see a seamless transition from 3GPP Long Term Evolution Advanced (LTE-A) towards heterogeneous wireless networks based on software-defined radio (SDR) concepts.



Nonlinear detection techniques offer resource efficient solutions in communication systems. The nonlinearity is adapted to the interference scenario, such that the interference is discriminated whereas the information of interest is detected largely unperturbed. Such communication systems are interference resilient.

One family of wireless systems features extreme bandwidths and low power spectral densities. These ultra-wideband (UWB) transmission techniques will revolutionize the communication among electronic sensors and actuators over short ranges in buildings. They cause little interference to existing small bandwidth systems. Here, the spectral efficiency is of less importance than the power efficiency of the transmission scheme in short-range links. Key applications will be low-power sensor networks and robust embedded systems which require neither batteries, nor external antennas. Thus, UWB technology provides a dependable association of data with objects: A key to the Internet of Things.

Univ.Prof. Ing. Dipl.-Ing. Dr.-Ing. Christoph Mecklenbräuker

Christian Doppler Lab „Wireless Technologies for Sustainable Mobility“

The Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility focuses on fundamental questions related to vehicular, cellular and short-range communication: connectivity, reliability, and availability. By a tight coupling of experimental work and design, we avoid simplistic assumptions on the communication channel statistics. We evaluate our designs on testbeds comprising real-world wireless communication environments. Thereby, we validate the devised algorithms in-situ. Key performance indicators for such wireless technologies are the reliability, the capability to meet strict deadlines, and coverage which we aim to achieve through multiple antenna transmission and reception. Our research plan consists of five modules: Vehicular Connectivity (with Kapsch TrafficCom AG), Smart Tags for Sensor Nets (with Infineon Technologies Austria AG), Mobile Communications Evolution (with A1 Telekom Austria AG and Kathrein Austria GmbH), Nearfield Power Efficiency (with NXP Semiconductors Austria GmbH), and Integrated Vehicle Chassis Antennas (with BMW Research and Technology and PIDSO Propagation Ideas and Solutions). The research in Module 1 focuses on reliable real-time wireless technologies in time–variant communication scenarios for safety-related applications. In Module 2, we investigate advanced transmission techniques for low energy consumption tags and aim at increasing the robustness of transmission in industrial environments. In Module 3, we measure and optimize multiuser throughput of multi-antenna transmission under delay constraints on the wireless channel and the novel inter-base station co-operative signaling. Further, we evaluate the potential gain from interference management for orthogonal frequency division multiple access (OFDMA). Efficient energy and data transmission for contactless identification is the central challenge in Modul 4 (started early 2012). In early 2013, a fifth module was started with the partners PIDSO Propagation Ideas and Solutions GmbH and BMW Research and Technology GmbH. In Module 5, the electromagnetic characteristics of carbon fiber reinforced composite materials are investigated, as they are in use for ultralight vehicular chassis for electromobility. Based in these results, multiple antennas for intelligent transport systems in electrical vehicles are desgined, optimized, and characterized.

Univ.Prof. Ing. Dipl.-Ing. Dr.-Ing. Christoph Mecklenbräuker

MOBILE RADIO

COMMUNICATION THEORY

OPTICAL COMMUNICATIONS

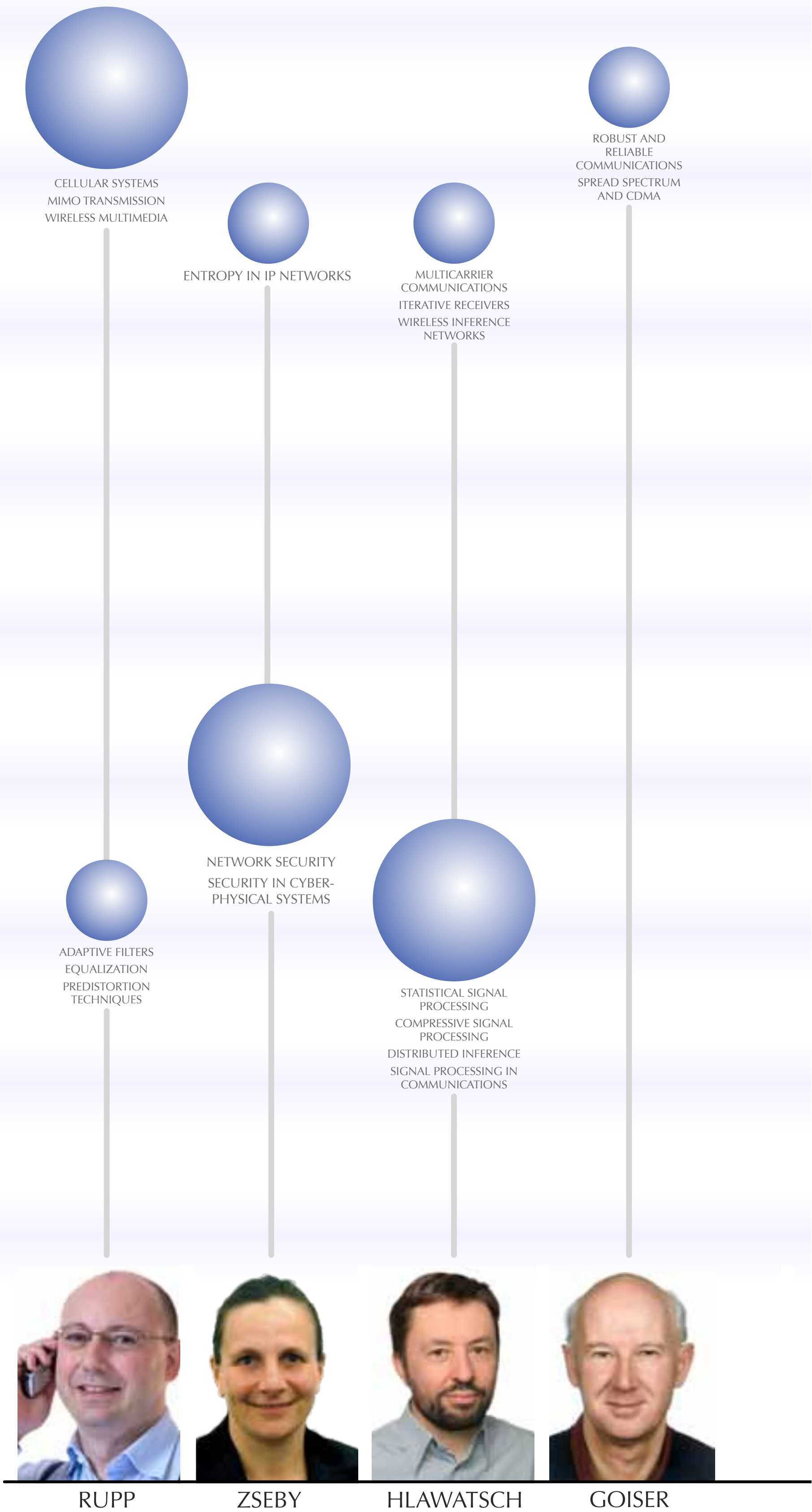
MULTIMEDIA SYSTEMS

RADIO FREQUENCY ENGINEERING

COMMUNICATION NETWORKS

SIGNAL PROCESSING

FLEXIBLE RADIO



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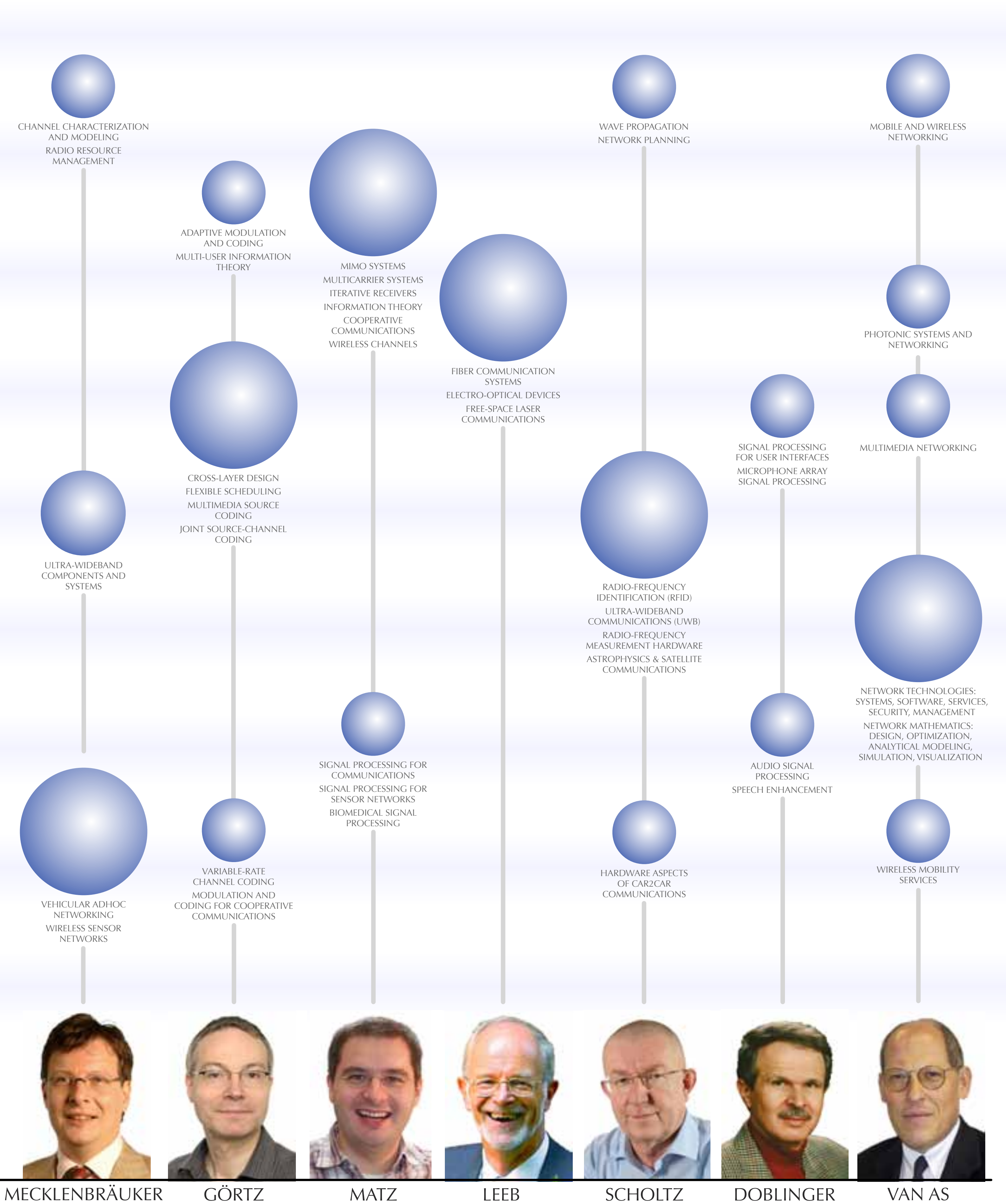

CHANNEL CHARACTERIZATION AND MODELING
RADIO RESOURCE MANAGEMENT
ULTRA-WIDEBAND COMPONENTS AND SYSTEMS
VEHICULAR ADHOC NETWORKING
WIRELESS SENSOR NETWORKS
MECKLENBRÄUKER
ADAPTIVE MODULATION AND CODING
MULTI-USER INFORMATION THEORY
CROSS-LAYER DESIGN
FLEXIBLE SCHEDULING
MULTIMEDIA SOURCE CODING
JOINT SOURCE-CHANNEL CODING
VARIABLE-RATE CHANNEL CODING
MODULATION AND CODING FOR COOPERATIVE COMMUNICATIONS
GÖRTZ
MIMO SYSTEMS
MULTICARRIER SYSTEMS
ITERATIVE RECEIVERS
INFORMATION THEORY
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WIRELESS CHANNELS
SIGNAL PROCESSING FOR COMMUNICATIONS
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BIOMEDICAL SIGNAL PROCESSING
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FIBER COMMUNICATION SYSTEMS
ELECTRO-OPTICAL DEVICES
FREE-SPACE LASER COMMUNICATIONS
LEEB
WAVE PROPAGATION
NETWORK PLANNING
RADIO-FREQUENCY IDENTIFICATION (RFID)
ULTRA-WIDEBAND COMMUNICATIONS (UWB)
RADIO-FREQUENCY MEASUREMENT HARDWARE
ASTROPHYSICS & SATELLITE COMMUNICATIONS
HARDWARE ASPECTS OF CAR2CAR COMMUNICATIONS
SCHOLTZ
SIGNAL PROCESSING FOR USER INTERFACES
MICROPHONE ARRAY SIGNAL PROCESSING
AUDIO SIGNAL PROCESSING
SPEECH ENHANCEMENT
DOBLINGER
MOBILE AND WIRELESS NETWORKING
PHOTONIC SYSTEMS AND NETWORKING
MULTIMEDIA NETWORKING
NETWORK TECHNOLOGIES: SYSTEMS, SOFTWARE, SERVICES, SECURITY, MANAGEMENT
NETWORK MATHEMATICS: DESIGN, OPTIMIZATION, ANALYTICAL MODELING, SIMULATION, VISUALIZATION
WIRELESS MOBILITY SERVICES
VAN AS

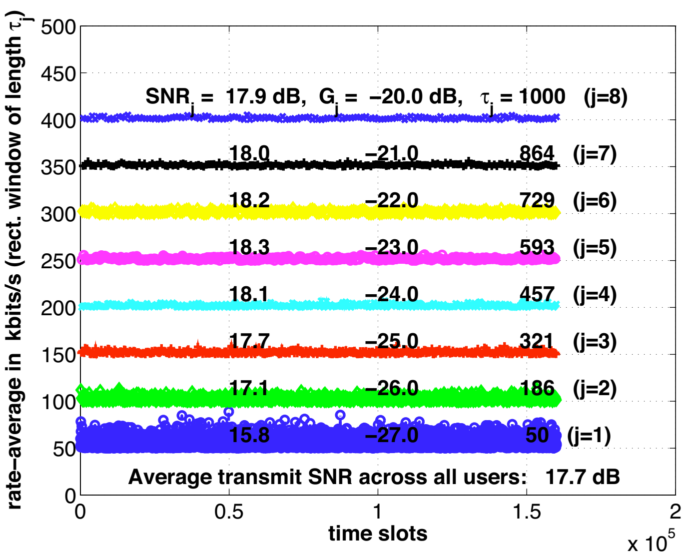
Multimedia Systems

Research in this field is about multimedia delivery efficiency in wireless networks under Quality-of-Service (QoS) constraints. The work involves multiuser information theory, source-channel coding and signal processing algorithms for user interfaces (e.g. audio signal processing such as noise reduction, beam-forming and echo cancellation) as well as Cross-Layer design such as multiuser scheduling concepts that exploit channel knowledge. The goal is to optimize the overall systems such that efficient use is made of the system resources, while the QoS demands of the users' applications are met. Closely related is work on error correction coding with adjustable rate to adapt to time varying channel conditions and on coding for optical wireless. Moreover, relaying and multihop transmission are considered to increase the capacity of cellular wireless systems.

Cross-Layer Scheduling

The classical design paradigm for communication networks is the Open Systems Interconnection (OSI) reference model; the basic notion is an independent design and a separate optimization of the network layers. The big advantage of this concept is its simplicity and universal applicability.

The drawback is that the best possible performance will not always be achieved by the classical OSI design, and this particularly applies to wireless networks, where "Multiuser Diversity" allows for very significant performance gains due to the fact that many users are served by the system who all have time varying channels: at least one of the channels is very likely to have high quality at any time instant, and the corresponding user should be served to achieve maximum rate at the lowest possible average transmit power. There is, however, a balance between this exploitation of multiuser diversity gains and the quality-of-service demands of the users. A good example is delay: if the latency constraints of an application are very stringent, there may not be the time to wait for a better channel, and in such situations the user will have to be scheduled for channel access even though the channel might be of bad quality. Of course this implies an "inefficient" use of more power, so there is a high-dimensional optimization problem to find the right trade-offs. Practical solutions in this field are guided by results from multiuser information theory that have to be adapted to the practical problems and be verified by computer simulations. An example is given in the figure below, with a performance plot of our newly developed Power-Controlled Cross-Layer Scheduling Concept that can meet hard delay constraints while performing close to the theoretical upper limits of information theory (ergodic capacity that ignores delay constraints). Our work in the field is not so much about specific applications such as video streaming but rather about universal principles, their theoretical analysis and their realization by algorithms of how to trade-off resource-efficiency and QoS demands whatever they may be. Part of our research is also on finite-lifetime channels that occur in car-to-car communications: transmission from one vehicle to another is characterized by a limited time span of a link between any two vehicles, so the total amount of information that (with limited power) can be communicated is limited and should be maximized by suitable scheduling that again has to exploit channel knowledge and even predictions on the development of the channel-coefficients.



The figure shows the average downlink rates over time of 8 users with rate requests of 50...400kbits/s achieved by the novel "Power-Controlled Cross-Layer Scheduler" (PCCLS). The rates are averaged over blocks of 50...1000 time slots (delay constraints). An outage occurs, whenever the block-averages drop below the rate requests. Independent fast Rayleigh-fading channels are assumed with long-term path losses of 20...27dB. The ratio of the overall transmit power required at the base station relative to the antenna noise at the receivers is 17.7dB. The information theoretical limit to achieve the rate requests (ignoring delay limits) is 16.3dB, while a conventional round-robin scheduler would consume 31.8dB.

Variable-Rate Channel Coding

Time varying channels require the transmitter to adapt to the currently available net data rate. For given modulation schemes this necessarily requires error correction coding with adjustable code rates. The classical approach is a combination of convolutional coding with puncturing, but conventional convolutional codes are not powerful enough. A good solution are Low-Density Parity-Check Convolutional Codes (LDPCcc) for which we developed a multi-step algorithm to find optimal puncturing patterns based on several criteria, including girth of the code graph, number of cycle trapping sets, and m-step recoverability. Starting from a good "mother code", the scheme allows to find families of rate-compatible LDPCccs that perform very well. The optimization method for the puncturing patterns is also based on our former work on cycle analysis for LDPC convolutional codes, which includes an algorithm to systematically find cycles of various lengths and their multiplicities.

Multi-hop Transmission and Relaying

Interference is the limiting factor in cellular wireless systems and, therefore, concepts that can reduce interference while even improving the service for all users are of great practical interest. Multi-hop transmission is a potential solution to the problem, as it allows a base station to use lower transmit power, as users at the fringes of a cell can be served by relays that forward the data to and from a user. Relaying, however, complicates the transmission problems very significantly, as not even the capacity of a single source-relay-destination system is known. Various relaying principles have been stated in the literature, and a new scheme recently considered is "soft re-encoding" at the relay: the idea is to keep the soft information received from the source and forward it to the final destination where all information about a transmitted codeword is eventually combined in one soft-decoder – the goal is not to lose information due to quantization in the relay. One result of our work is that soft encoding brings only benefits when applied in a turbo-like structure with iterative decoding at the receiver, because the soft values, when their signs are incorrect, will not push the iterative decoder so easily towards an incorrect code word. In terms of mutual information between the original codeword and the re-encoded soft codeword at the relay we could, however, not find benefits of soft encoding over hard encoding. We found that the better performance of soft re-encoding in a turbo-coded structure can equally be achieved by hard encoding complemented by an error detecting cyclic redundancy check, which prevents relayed data from being used at the destination when the data contains errors; the latter scheme is by far simpler than one employing a soft re-encoder.

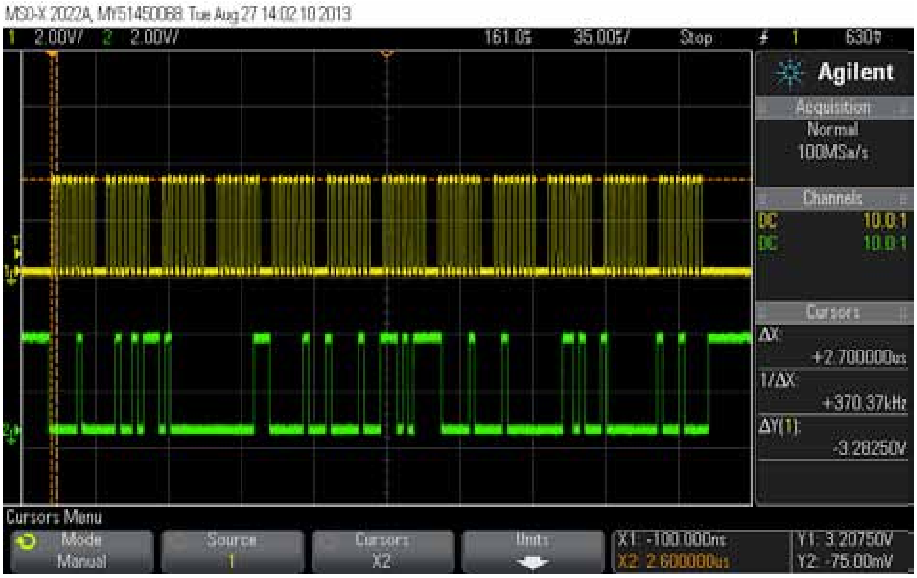
Further work in the field of relaying was on analytical performance prediction. We managed to find a new series representation for modified Bessel functions that appear in the performance equations for the source-relay-destination link. Those Bessel functions don't allow for closed-form analytical expressions for bit error rates and outage capacities of the complete system, but with our new series representation we could give very accurate closed-form expressions that match simulation results perfectly. Finally, we considered mutliple-antenna relays and investigated transmit beam-forming. One major new result is a characterization (and the corresponding proof) of the SNR region in which transmission in the direction of the largest eigenvector of the channel matrix is optimal.

Coding for Optical Wireless Channels

Recently, staircase codes have been proposed in the literature. Those are high-rate codes designed for optical transport networks (ONT) and they allow for extremely high throughput at low complexity. They organize the data symbols in square block of data, with row- and column-wise (horizontal and vertical) encoding by simple BCH codes. The "horizontal" redundancy bits are part of the data blocks for "vertical" encoding and vice versa, leading to a staircase-like structure of the code. Due to the high speeds in optical transmission stringent low-complexity requirements exist, so hard decision decoding is the method of choice. The code construction allows for pipelined and parallel iterative decoding which is highly efficient, and, hence, the coding scheme beats all current standards for ONT very significantly. Our idea is to extend staircase codes for wireless optical transmission, which will require lower and flexible code rates. Moreover, wireless channels tend to produce burst errors (e.g. due to link blockages) so the coding scheme must also be adapted to those requirements, e.g., by replacing the BCH component codes by Reed-Solomon codes.

Programmable Hardware

The coding schemes investigated in our research are designed for low error rates, which is particularly true for wireless optical transmission. As it is impossible to obtain statistically significant results for bit error rates below 10^{-6} by computer simulations, we also implement coding schemes in programmable hardware (Field-Programmable Gate Arrays, FPGAs) to obtain real measurement results for very low error probabilities. We have built up significant expertise in this field and we also provide specific programmable circuits based on micro-controllers and FPGAs to other research groups, e.g. for research in radio frequency identification tags. Another, very recent line of work is to build simple network nodes to study synchronization mechanisms and data distribution in ad-hoc networks.



The figure shows in the upper plot the clock signal and in the lower plot the data output of a serial peripheral interface transmitting 12 blocks of data for the internal registers of a waveform generator integrated circuit in a testbed controller for Radio-Frequency Identification (RFID).

Univ.Prof. Dipl.-Ing. Dr.-Ing. Norbert Görtz

Communication Theory

In this area, our activities deal with physical layer aspects of wireless networks and with distributed algorithms for sensor networks. Our research has been funded by the Viennese Science and Technology Fund (WWTF) via the projects "Distributed Information Processing in Wireless Sensor Networks" and "The Information Bottleneck Principle in Multiterminal Communication and Inference," by the Austrian Science Fund (FWF) via the project "Information Networks" within the National Research Network "Signal and Information Processing in Science and Engineering," and by the European Union via the FP7 FET project "Enhanced Interference Alignment Techniques for Unprecedented Spectral Efficiency" (HIATUS) and via the FP6/FP7 project "Network of Excellence in Wireless Communications" (NEWCOM).

Interference Management

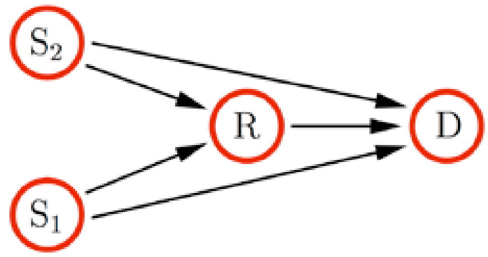
Radio interference is becoming a major transmission impairment in wireless networks, hence necessitating advanced interference management schemes. Interference alignment (IA) is a very recent and promising paradigm in this context. IA promises new degrees of freedom that allow more parallel interference-free transmissions within the same spectrum.

We have assessed the ergodic mutual information of IA in ad-hoc networks with random node positions. Furthermore we specifically studied partially connected networks, for which we have developed specific IA feasibility conditions. We have considered the application of these results to cellular networks and quantified the performance in this context. We studied the sum-rate maximization problem as the medium-SNR counterpart of IA and developed low-complexity precoder optimization techniques based on a Grassmann manifold representation. Finally, we developed a sum-rate maximization scheme that is robust to channel uncertainty. Another challenge of IA is provisioning of channel state information (CSI) to the devices involved. We thus have studied channel quantization methods for IA. Specifically we have devised quantization schemes that exploit the problem invariants (channel scaling and rotation) to reduce the amount of feedback. This technique was applied in cellular systems for over-the-air channel state feedback and CSI sharing between base stations over the backhaul (the latter resulting in a patent application with Ericsson).

Relay Networks

In the multiple access relay channel, several sources communicate with a single destination with the help of a relay. For such scenarios, we have investigated relaying strategies that combine compress-and-forward with network coding. The compression at the relay is achieved by quantizing log-likelihood ratios (LLR) of the information bits of all sources. The quantizers have been designed to maximize rate by using the so-called information bottleneck principle. At the destination, an iterative joint network-channel decoder is used to recover the source data. The overall scheme can be applied to scenarios with more than two sources and asymmetric channel conditions. We furthermore proposed extensions of this scheme to multiway relay channels.

Decode-and-forward is an alternative relaying strategy in which the source data is decoded and re-encoded (possibly in combination with a network code) at the relay. We have studied decode-and-forward in the multiple access relay channel for the case where the data of the sources is correlated. Specifically, we proposed a scheme that is based on bilayer spatially coupled low-density parity check (SC-LDPC) codes. Joint source-channel coding with joint channel decoding is used to exploit the correlation. Modeling the links between the nodes as binary erasure channels, we obtained analytical bounds on the achievable rates and we proved that the proposed coding scheme achieves the Shannon limit for symmetric channel conditions and uncorrelated sources. Using density evolution, we demonstrated that our scheme approaches capacity also for the non-symmetric and correlated case.



In collaboration with Nokia we have developed distributed beamforming schemes for relay networks in which multiple relays assist a source. We proposed an iterative scheme for updating the beamforming weights using additive or multiplicative perturbations and 1-bit feedback from the destination.

Precoding

Multi-antenna precoding at the base station is an attractive solution for increasing the throughput in cellular systems in spite of low terminal complexity. We have shown that under a variety of practical constraints (CSI quality, finite-rate feedforward/feedback, and dynamic range), classical vector perturbation features an undesirable error floor. This motivated us to propose “transmit outage precoding,” a modification that avoids feedforward by abstaining from transmission when channel conditions prohibit reliable reception anyway. The receivers’ limited dynamic range can be accounted for by using a restricted set of perturbation vectors at the transmitter. We have shown analytically that our scheme achieves the same diversity order as conventional vector perturbation in idealized conditions and that CSI accuracy is the most critical factor impacting diversity order.

Demodulation

In multiple-input multiple-output (MIMO) systems using spatial multiplexing, the demodulator (detector) provides the channel decoder with LLRs. An important concept in that context is lattice reduction, i.e., the computation of improved lattice bases where the lattice is defined by the channel matrix. We showed that in the context of MIMO detection and precoding, Seysen reduction and Brun’s algorithm are serious contenders of the LLL algorithm.

To avoid the problem that demodulator comparisons in terms of BER depend on the structure and the rate of the chosen code, we proposed mutual information as an alternative performance metric that measures the maximum rates achievable with a specific MIMO demodulator. Somewhat surprisingly, it turned out that often there is no universal performance ranking, i.e., which demodulator is preferable depends on the SNR and on the rate. More recently, we have discovered a method that can be used to estimate the mutual information as well as the bit error probability in a fully blind fashion, i.e., without any training data. The method essentially relies on soft information in the form of LLRs.

In practical systems, LLR values are stored with finite precision. Thus, LLR quantization is a key requirement. We have proposed optimal LLR quantizers that build on the information bottleneck method and maximize the rate achievable over the end-to-end channel. We have furthermore devised MIMO receivers that integrate soft demodulation based on sphere decoders and MMSE equalizers with LLR quantization in an efficient manner.

Iterative Receivers

Turbo-style receivers consist of two or more stages that exchange soft information (bit probabilities or LLRs) to improve performance.

Using factor graphs and the sum-product algorithm, we devised a receiver for interleave division multiple access (IDMA) systems; this receiver iteratively performs channel estimation, multi-user detection, and channel decoding. Using Gaussian message approximations, we achieved significant complexity savings without compromising performance.

Furthermore, we considered bit-interleaved coded modulation (BICM) with iterative demodulation in situations with imperfect channel state information (CSI). Here, we derived optimum metrics for the demodulation stage that take into account the statistics of the channel estimate. These demodulators were assessed using extrinsic information transfer charts. By optimizing the degree distribution of LDPC codes, we obtained improved performance.

Both for IDMA and BICM, we developed selective message update schemes in which the iterative receiver updates only “unreliable” LLRs. Surprisingly, this not only entailed a graceful complexity reduction but also showed the potential to improve the error probability, in particular when used in conjunction with iterative channel estimation.

Multicarrier Systems

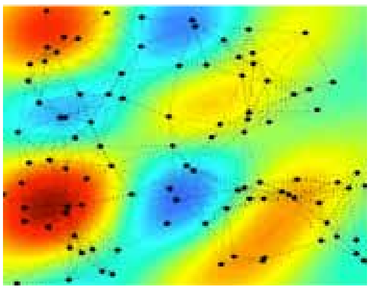
Channel estimation and equalization is a crucial part of receiver design in multicarrier systems.

We considered intercarrier-interference free OFDM systems that use irregular pilot patterns within a frame (this model encompasses WiFi, WiMAX, and LTE). In order to estimate the channel coefficients, we applied the mathematical theory of non-uniform sampling and developed corresponding channel estimation algorithms that are both efficient and accurate.

In systems with high mobility (vehicular, high-speed trains), multicarrier systems may suffer from intercarrier interference that results from physical Doppler effects. Using suitable polynomial basis expansion models, we derived computationally efficient channel estimators and corresponding channel equalizers. These equalizers build on iterative solvers for linear systems of equations and exploit the structure of the underlying channel matrix.

Sensor networks are a promising paradigm for various monitoring tasks. Distributed algorithms are at the heart of any sensor network architecture.

Distributed Field Reconstruction



In the context of the reconstruction of spatiotemporal fields from sensor network measurements, we proposed to use shift-invariant spaces instead of band-limited spaces. The associated reconstruction algorithm scales only linearly with the number of sensors. In addition, we demonstrated that field reconstruction based on shift-invariant spaces is less susceptible to localization errors of the sensor nodes. In follow-up work we considered the resource allocation problem for distributed estimation schemes under analog transmission of the measurements. Transmit power allocation can be phrased as a convex optimization problem that can be solved using standard algorithms.

In many applications, the field to be estimated can be modeled in terms of partial differential equations. Based on a spatiotemporal discretization of the physical model, we developed Bayesian field estimators that use a distributed particle filter to take into account the nonlinear and non-Gaussian nature of the model. The method was specialized to the case of acoustic fields with the goal of tracking the position and strength of acoustical sources. We augmented our scheme with a compression strategy in order to reduce the amount of data to be exchanged between the sensors and we derived Weiss-Weinstein bounds to assess the performance of our distributed field estimators.

Consensus Algorithms

Consensus schemes are algorithms for distributed averaging that are instrumental in many sensor network applications. Two such schemes are average consensus (AC) and consensus propagation (CP). We proposed a CP variant that uses broadcast transmissions and an ALOHA-like protocol. This variant of CP tolerates a significant fraction of message losses due to collisions. We furthermore extended CP to be applicable to dynamic scenarios in which the acquisition and averaging of measurements are fully integrated.

For AC, we developed a weight design that is motivated by fluid dynamics and superimposes an advective flow on conventional AC. This design led to significantly improved convergence. Another AC design morphs back and forth between different weights and thereby allows AC to adapt optimally to the measurements. Finally, we studied the impact of node mobility on the performance of AC. We provided analytical and numerical evidence that mobility can drastically improve AC convergence.

Ao.Univ.Prof. Dipl.-Ing. Dr.techn. Gerald Matz

Optical Data Transmission

The Internet would be unthinkable without optical data transmission: Only this technology makes possible to transmit the enormous amount of data which is the very basis of today's society. To this end, a net of glass fibers covers our globe, not only on the continents but also in the depths of the oceans. Laser beams also bridge by far larger distances, e.g. in communication links between satellites and to space probes. At the other end of the scale one finds optical waveguides only a few millimeters or centimeters long, which connect electronic devices at Terabit/second data rates, with negligible electromagnetic interference but with high efficiency.

Optical Printed Circuit Boards

Together with the company AT&S we developed integrated optical data links for circuit boards. With this concept the light guidance occurs in a thin layer of a polymer, into which an optical waveguide has been inscribed using two-photon absorption. The waveguide connects electro-optic devices mounted on a multi-layer circuit board, i.e. VCSELs (vertical-cavity surface-emitting lasers) and photodiodes. Our task within this project sponsored by the Austrian Nano-Initiative consists of characterising the devices involved with respect to their data transmission properties at a wavelength of 850 nm and in determining the maximum data rate that can be achieved with this technology. For the typical case of a waveguide length of 10 cm we could transmit easily data rates of several Gbit/s, even when employing flexible substrates (see photograph).

Photograph of flexible electro-optic board equipped with SMA connector interfaces, demonstrating bending with a radius of 1.5 cm.

Large-Area Laser Displays

With an Austrian startup company we began a cooperation towards the development of large video screens for three-dimensional displaying. The principle used is autostereoscopy, a technique that creates three-dimensional images with the viewer, without requiring special glasses. Employing lasers as light sources allows implementing very large displays that convey a bright and colorful impression even outdoors and at full sunlight. We provided and strengthened our know-how in the field of driving semiconductor lasers and micro-mirrors and also performed the experimental characterization of the entire opto-electronic system.

Univ.Prof.i.R. Dipl.-Ing. Dr.techn. Walter Leeb

Radio Frequency Engineering

In the field of Radio Frequency Engineering we are primarily involved in experimental research. Radio Frequency Engineering methods have to be applied when the mechanical size of the building blocks becomes comparable to the operating wavelength of devices.

Antenna Characterization – Anechoic Chamber

During the last years the Institute has set up a laboratory for antenna characterization, mainly in order to expand the research opportunities and in response to the trend towards multi-band antennas/multiple antennas for the next RFID generation as well as ultra wideband radio interfaces. This lab is also intended to be used for educational purposes in the Major Telecommunications. In this context, a shielded, anechoic room (a so called anechoic chamber) was built, where novel antenna designs can be characterized. Possible characterization parameters are the radiation pattern, polarization, gain, equivalent isotropic radiated power (EIRP), and efficiency of an antenna, to name the most known antenna parameters.

This new antenna measurement chamber contains a three-dimensional spherical near-field scanner. In particular, the near field on a sphere around the antenna under test (AUT) is recorded at sampling points and the radiation characteristic is determined by means of a near-field far-field transformation (NFFFT). This is realized by two rotary stages supporting 330° rotation in the theta angle and full 360° rotation in the phi angle. Additionally, a third rotary stage allows for measurements in orthogonal linear polarizations. The rotary stages allow for a step size of 0.004° with an accuracy of 0.1°.

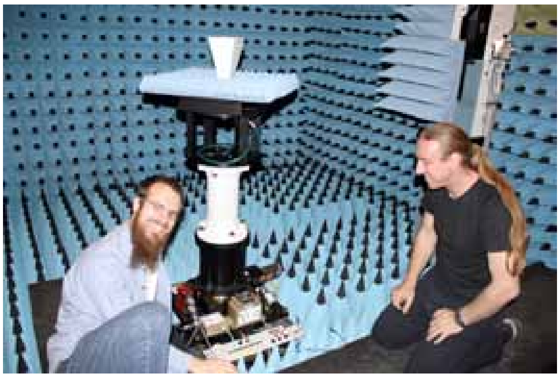


Figure 1 Preparation for an antenna measurement inside the anechoic chamber

The system supports a frequency range from 800 MHz to 40 GHz and also the characterization of passive as well as active AUTs where the de-vices may have a diameter of up to 1.5 m and a maximum weight of 900 kg. Two double ridged horn antennas are used as probe antennas. One covers the frequency range from 800 MHz to 10 GHz and the second probe antenna allows for measurements up to 40 GHz.

After completed calibration and preparations, the measurement itself runs automatically. An integrated video system allows for visual observation of the measurement from outside the chamber. A dedicated measurement computer controls all the rotary stages and the measurement devices. A vector network analyzer (PNA-X) acts as transmitter and as receiver in this measurement system. For each frequency point and polarization a data set is recorded on the computer. Data processing is done offline after the measurements are completed.

Finally, the system is fully air conditioned for stable temperature and humidity condition during the measurements.

Figure 2 Operation center outside the anechoic chamber

Radio Frequency Identification - RFID

RFID in sensor networks bring major benefits in different applications. In this context, the research group radio frequency techniques focuses on applications that use passive radio communications which are based on the so-called backscatter modulation. One application was investigated in the course of an FFG project. The focus of this project was on the wireless transmission of data between a reader and sensors (tags), including their antennas, attached directly on car tires. The main challenge here is the high influence of the tire's shape and material on the antenna characteristics, which has been analyzed in the course of this project.

Another application is on- body communication, which is based on the network concept Wireless Body Area Network (WBAN). Here, the sensors (tags) that are attached to the body communicate with each other and / or with an external reader. In this context, the research group has carried out channel measurements for both cases, namely to characterize the channels located on the surface of the body as well as those that pass right through it.

The strong trend towards further miniaturization and higher integration of electronic and mechanical components leads to challenges concerning their energy efficiency or rather their losses and efficiency, the communication range, the antenna design, and the methods of measurement/the measurement accuracy in the course of e.g., antenna characterization. In this sense, the research group participated in an industrial project that had its focus on the experimental analysis of compact antennas for miniature RFID tags with the size of a few square millimeters. Prototypes were manufactured by the industrial partner, whereas the prototypes consisted of an UHF receiver and a broadband pulse transmitter. The research group studied in its radiation characteristics and investigated in possible measurement techniques.

Multiple antenna techniques are a main part of the Radio-Frequency Engineering group's research focuses. Regarding RFID, the research team set up a test environment using an RFID reader, developed at our institute especially for this purposes. It consists of a digital baseband module, modular RF frontends and multiple transmit and receive antennas. The crosstalk between the sender and the receiver is minimized by techniques that were also developed by the research group. This increased the sensitivity of the receiver and thus, the maximum communication range.

Satellite Communications

During the last few years we have set up a modular, fully autonomous and remotely controllable satellite ground station. The antennas (Figure 3) are located at the flat roof of our building, while the indoor radio equipment and computer control have been set up in an air-conditioned room in the 6th floor (Figure 4). After successful testing of our ground station using the Canadian satellite MOST (Microvariability and Oscillations of Stars) and also the French satellite COROT (Convection, Rotation and planetary Transits) it is now being reconfigured. We will possibly be able to act as one ground station for the BRITE (BRIght Target Explorer) CONSTELLATION mission. This project is performed by the Institute of Communication Networks and Satellite Communications at the Graz University of Technology and by the Institute of Astrophysics at the University of Vienna. Its goal is examination of bright stars with the aid of low-cost instruments. This allows to do research and teaching in the field of space technology at affordable costs. Our intention is to provide an additional ground station in order to enhance data download performance within the satellite network.

Figure 3 Antenna system of the multi satellite ground station on the roof of our institute.

Here is a brief summary of the properties of the TU Vienna Satellite Ground Station: The antenna system comprises a 3.7m parabolic dish for 2GHz, and a set of Yagi-Uda arrays for 150MHz and 440MHz. Flexible satellite position determination and automatic pass scheduling have been implemented. Linear low-noise RF front ends and linear amplifiers for the VHF/UHF/SHF frequency bands are available. Full-duplex operation is possible in-band and cross-band. Data transmission supports modulation schemes up to 16QAM, hence all major scientific satellite missions can be served.

Our satellite ground station is designed to be expandable and updateable for scientific data down-load in the context of future research satellite missions. Many universities are presently building and launching microsatellites, but lack experience and facilities to communicate with them. Here we can offer assistance. Last but not least, our ground station is regularly used in student lab exercises on satellite communications.

Figure 4 Indoor equipment of the ground station.

Ao.Univ.Prof.i.R. Dipl.-Ing. Dr.techn. Arpad Scholtz

Speech and Audio Signal Processing

Our research activities in this area have been focused on two topics: Active noise cancellation (ANC) used in headphones, and real-time simulation of special nonlinear audio systems. ANC is used to reduce the influence of disturbing sounds like engine noise in air plane cabins. In cooperation with an Austrian company, we have investigated different adaptive signal processing algorithms to suppress environmental noise during playback of audio signals via headphones. Simulations have been carried out with MATLAB®, and a hardware system using a 16 bit fixed-point digital signal processor has been designed. This system is used to evaluate ANC systems in real-time with different laboratory headphone prototypes.

In the field of nonlinear audio systems, we have worked on modeling the sound characteristics of tube preamplifiers by means of digital signal processing techniques. Applications include amplifiers for guitars and microphones used in digital music production studios. Based on amplifier circuit schematics, a nonlinear state-space representation is employed to efficiently simulate the connected amplifier stages. Real-time operation is ensured by several refinements like the usage of lookup tables to model the nonlinear tube characteristics. In addition, the interaction between amplifier stages due to finite input impedances is eliminated by an iterative computation of the state-space variables. The final real-time implementation is written in C++ using vectorized matrix operations.

Ass.Prof. Dipl.-Ing. Dr.techn. Gerhard Doblinger