INSTITUTE OF TELECOMMUNICATIONS
TU WIEN

RESEARCH ACTIVITIES
2014 – 2018

TECHNISCHE UNIVERSITÄT WIEN

institute of telecommunications

Preface

This report summarizes the research and teaching activities at the Institute of Telecommunications at TU Wien for the years 2014 - 2018. During the past four years we were able to accomplish many achievements together. We acquired many new research projects, either funded directly by industry or by national or international funding agencies. In 2016 we concluded the very successful seven years of the CD Lab on Wireless Technologies for Sustainable Mobility, which focused on different aspects in vehicular, cellular and short-range communication. In 2017 we started a new CD Lab on Dependable Wireless Connectivity for the Society in Motion. The new CD Lab will address research questions relevant for providing solutions for the new fifth generation (5G) wireless networks.

With support of TU Wien we established a new lab for Future Self-Organizing Energy Networks (FUSE) in cooperation with the Institute of Energy Systems and Electrical Drives and could already acquire several projects in the area of critical infrastructure protection.

We expanded our teaching activities and offered new classes that attract students not only from telecommunications but also from other master programs and even from other faculties. We also started a long-term collaboration with the Brno University of Technology (BUT). The collaboration consists of several joint projects and as part of the cooperation we established a Joint Master Degree Program in Telecommunications.

I would like to thank all the members of the Institute for the good work and their commitment. The scientific personnel achieved excellent results in different research activities in the field of telecommunications that resulted in many publications in high quality journals and conferences. Also, many of our retired colleagues remain active in research and provided useful support to research and teaching based on their valuable experience. The non-scientific personnel, secretaries, institute assistance and administrative staff built the foundation for smooth operations and always performed reliably in a highly dynamic environment. I also would like to thank all our project partners from industry and academia for the productive cooperation and the funding agencies for their continuous support.

The past five years of the institute were full of successful projects, rewarding research, and prosperous teaching activities and I am confident that with our team and our partners we can continue this successful path in the future.

Vienna, August 2019

Tanja Zseby

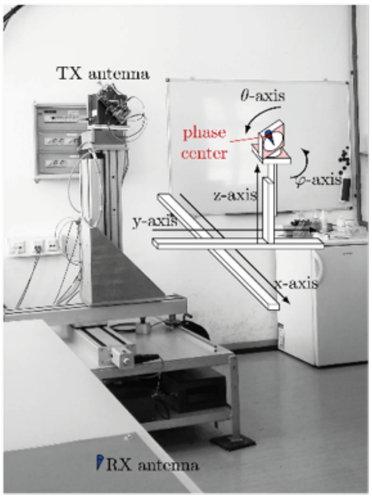
Tanja Zseby
Head of Institute

1. Mobile Communications

The Mobile Communications Group has grown substantially over the years, covering experimental work in our MIMO Labs, theoretical and simulation work in the context of link and system level design as well as mobile broadband performance methods. The group was split into two subgroups, one being the newly founded Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion led by Dr. Stefan Schwarz, the other the Mobile Broadband Performance Group led by Dr. Philipp Svoboda.

1.1 Channel Characterization and Modeling

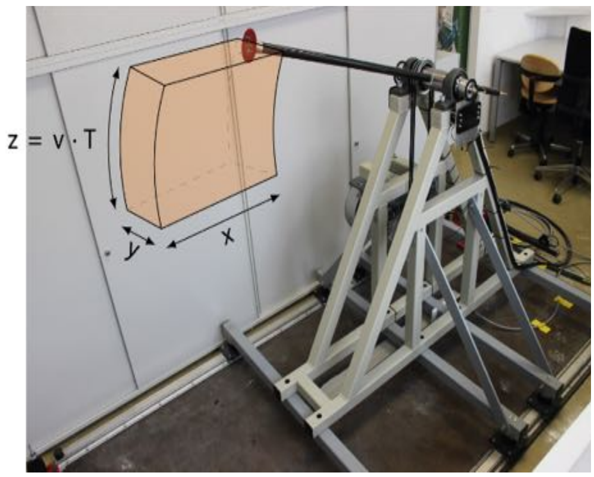
Mobile Channel Analysis and Modelling in the Millimeter Wave Band



Measurement setup to enable automatic spatial sampling of the wireless channel in the mmWave band.

Wireless transmissions in the millimeter wave (mmWave) band exhibit great potential for future mobile communication systems, since large amounts of untapped spectrum are available in this band. However, the channel characteristics in the mmWave band are not yet sufficiently well understood and therefore measurement campaigns are conducted worldwide by many research groups. Our research group also contributes to these efforts, by performing mmWave channel characterizations both in indoor and outdoor transmission scenarios, in order to derive statistical channel models for various propagation conditions.

Repeatable/Controlled Measurements at High Velocity



Test-bed to support controlled and repeatable high velocity channel measurements.

Measuring the physical layer performance at high velocity in real-world scenarios is conceptually straightforward when using off-the-shelf test equipment in so-called drive-by measurements, employing cars, trains or even planes as test-beds. Such measurements, however, do not allow for controlled repeatable experiments, since the environmental conditions are inevitably changing in-between multiple test runs. In our research group, we have developed a rotary test-bed that supports controlled and repeatable measurements at high velocities. This test-bed facilitates the performance investigation under identical environmental conditions except for the one single physical layer parameter whose effect is being tested and analyzed.

Full-Dimension/Massive MIMO Virtual Antenna Array Measurements

Virtual full-dimension MIMO measurement test-bed.

Full-dimension/massive MIMO system utilize large-scale two-dimensional antenna arrays to achieve a large spatial resolution, promising significant spatial multiplexing gains in future mobile communication systems. To validate these promises under real world conditions, we conduct full-dimension MIMO measurements at our Institute. We thereby apply a so-called virtual full-dimension MIMO transmit antenna array, which is formed by moving a cross-polarized dipole antenna along the vertical and horizontal axes through an automated positioning system. This approach allows us to emulate virtually any full-dimension MIMO antenna array geometry (within the limits of the positioning system) and thus provides the opportunity to investigate the impact of antenna array dimensions, in terms of spacing and number of antenna elements.

Spatially Consistent Three-Dimensional Channel Modeling

At our institute, we develop enhancements of so-called stochastic geometric channel models, which support spatially consistent three-dimensional channel modeling. Such models are required for computationally efficient and realistic performance investigation of novel full-dimension/massive MIMO technologies by means of system level simulations. Our methods provide spatial consistency of macro- and microscopic channel fading parameters and have been validated through extensive computationally highly demanding Ray tracing simulations.

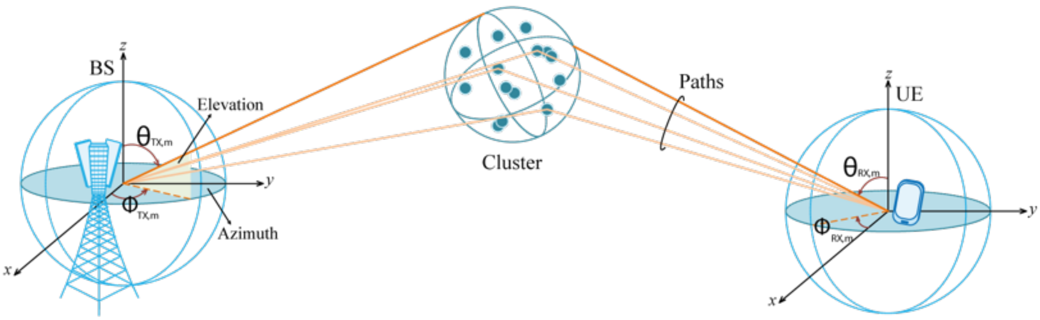
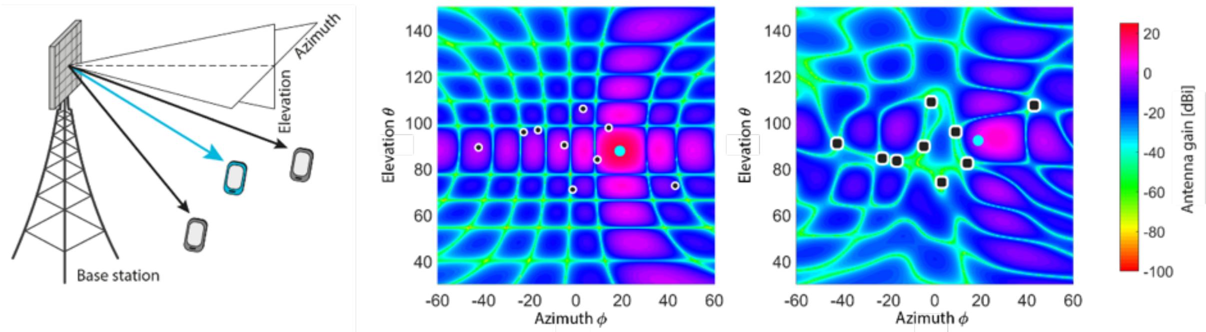


Illustration of three-dimensional channel modeling based on spatially distributed scattering clusters.

1.2 Link and System Level Analysis and Optimization

Link Level Signal Processing and Transceiver Optimization

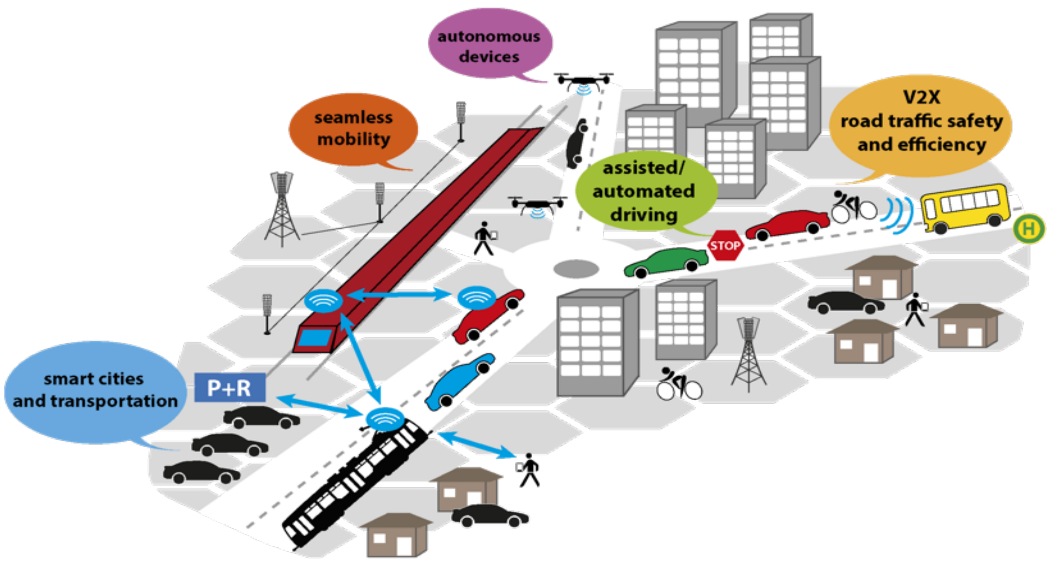
In our mobile communications research group, we conduct physical layer research for mobile wireless communication systems of the fifth and even the sixth generation (5G and 6G). We develop robust high performance antenna array signal processing methods for full-dimension/massive MIMO systems, investigate the potential of non-orthogonal multiple access techniques, and optimize the performance of novel transmission waveforms. The combination of these methods promises significantly enhanced throughput, reduced transmission latency and improved reliability of the wireless connectivity.



Antenna array response of an adaptively beamformed full-dimension MIMO antenna array.

Heterogeneous Cellular Networks and Cellular-Assisted Vehicular Communications

Cellular networks become increasingly heterogeneous to cope with the various demands imposed by the applications envisioned for future mobile communication systems. Future cellular networks will not only serve human users, but will increasingly be utilized for so-called machine type communication scenarios, such as vehicular communications. The evaluation of such heterogeneous cellular networks requires sophisticated tools, combining advanced mathematical analysis with elaborate computer simulations. In our research group, we perform such investigations by applying tools from stochastic geometry and random shape theory and benchmarking our analysis against complex system level simulations.

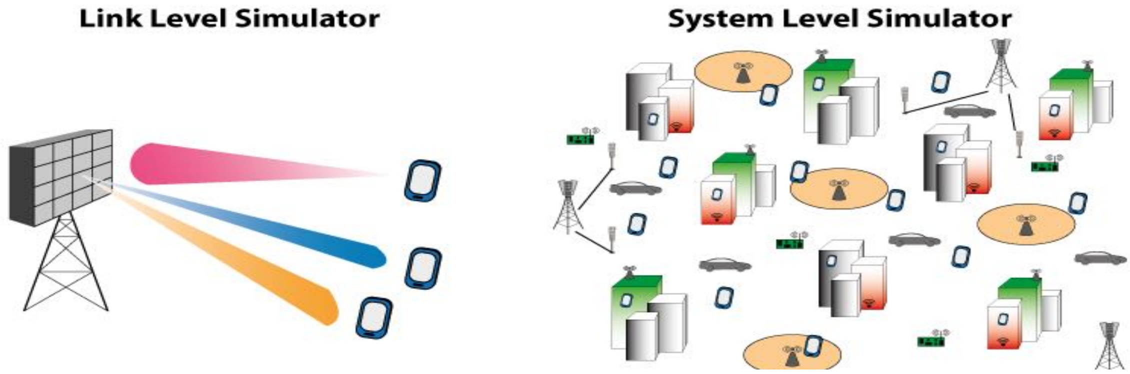


Vehicular communication use cases in 5G and beyond mobile communications.

Univ.Prof. Dipl.-Ing. Dr.techn. Markus Rupp, Dipl.-Ing. Dr. Stefan Schwarz, Dipl.-Ing. Dr. Philipp Svoboda

The Vienna 5G Simulators

Link and system level simulations build the basis for accurate and realistic performance investigation of mobile communication systems. They are indispensable for rapid prototyping of novel signal processing methods and enable benchmarking against state-of-the-art standardized approaches. In our mobile communications research group, we develop sophisticated link and system level simulation methodologies and abstraction techniques and apply them for standard compliant simulation of 3GPP cellular communication systems. This approach provides the means to analyze novel signal processing methods on link level and network optimization techniques on system level within standard compliant simulation environments, in order to gauge their value under practical conditions.

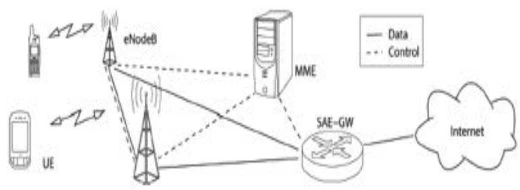


Point-to-point link level simulations vs. large-scale system level simulations.

1.3 Characterization of the Wireless Internet Access

In the group of Mobile Broadband Measurement, we focus on benchmarking mobile networks. Benchmarking is the practice of comparing the performance of a company, institution, tool, or methodology to competitors, similar businesses or the general state of the art in the field, most preferably to what is considered to be the best or most successful in practice, in order to reach the standards achieved by this reference and increase the quality of own operation. Mobile network benchmarking can be undertaken by mobile network operators for deployment, operation and maintenance purposes, as well as regulatory bodies for monitoring the networks of different operators for quality assurance and network neutrality. A Quality of Service (QoS) assessment methodology for mobile communication networks, focused on end user perception of quality must be independent of the access technologies implemented by the mobile networks.
In our research group, we have developed methods to support swift, reliable and distributed measurements of performance in mobile networks for static, nomadic and high speed user scenarios.

(Resourceful) Active Probing



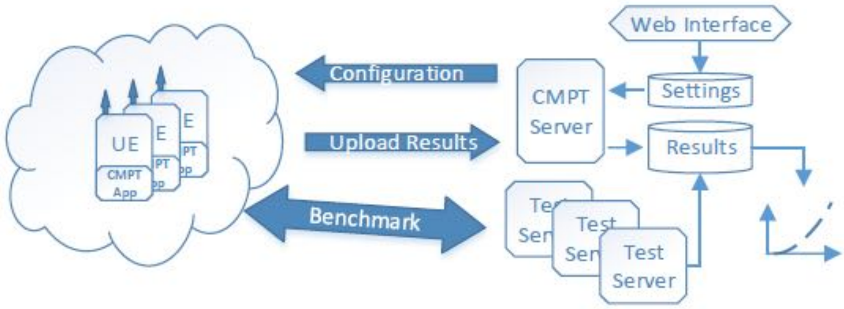
Downlink throughput measurements in cellular mobile networks are of interest not only for researchers but also for mobile network operators and end-users. Conventional smartphone applications measure the throughput by downloading as much data as possible for a predefined duration, consuming tens of megabytes per measurement and blocking Internet connections for several seconds. Fast low-volume probing saves users' data. It also allows for more frequent measurements, leading to higher spatial resolution along a measurement path, e.g. in case of vehicular measurements.

Self-driving cars require reliable connections; swift measurements would enable a constant monitoring without severe service interruptions.

We analyze a possible reduction of data volume per test and develop software solutions for these case that allow comparing the estimated throughput to a conventional, heavy load methodology in practice. Measurements with a user equipment (UE) in live cellular mobile networks have a potential of characterizing real users' experience but suffer from limited repeatability (small-scale fading, quickly changing cell load, varying interference from neighboring cells). To circumvent this restriction and allow validation of new methodologies, we performed measurements in a controlled LTE cell. We currently are able to achieve throughput estimates comparable to conventional apps in much shorter time (less than 50 ms) requiring much lower data volume (less than 2 MB). This enables us to retrieve high spatial and temporal resolutions in test-drives.

The measurement setup is part of the CMPT Framework for Reference Measurements (crowdsourcing mobile performance tool). It is an Android-based Application that allows to perform automatized performance measurement tasks. It executes pre-defined experiments and reports results to a centralized database system. This enables continuous monitoring and drive testing.

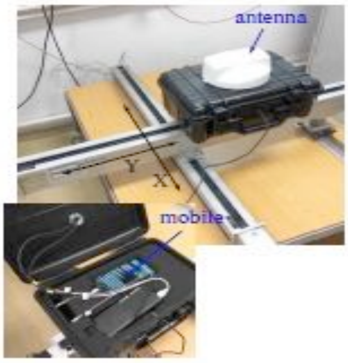
Benchmarking LTE Networks Using Crowdsourced Measurements



In recent years, the trend in mobile network benchmarking has shifted towards crowdsourced measurements – measurements performed by anonymous end-users. While being a resourceful alternative to drive tests, crowdsourcing lacks repeatability, testing strategy and setup control, generating tests in random locations at random time points, often reflecting users' tariffs rather than networks' performance. At the institute we have generated the infrastructure to conduct, trace and process crowdsourced measurements. In addition to this we have imported all available open-data from Austria, Slovakia, and taken part in the MONROE H2020 project.

So far the state of the art in benchmarking on top of open-data relies on throughput medians among operators based on all available crowdsourced tests. Such analysis cannot consider circumstances under which measurements were performed and is thus biased. To tackle these problems we are and have developed a set of methods method which characterizes networks' throughput performance as a function of received signal strength. This is achieved by filtering for throughput-degraded measurements and applying a nonlinear model our approach reaches very good quality of fit and outperforms current linear solutions. Methods are validated with real world measurement campaigns as well as lab results in anechoic rooms.

Field Experiments for Swift Performance Benchmarking



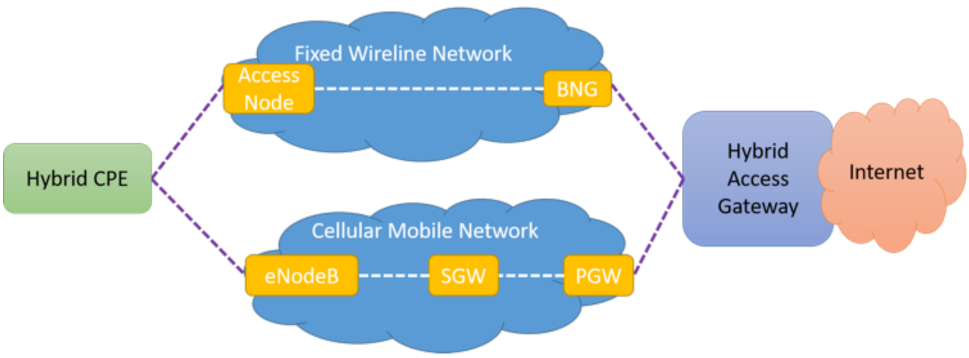
There are several Key Performance Indicators (KPI) impacting the end user perception of network communication links, one important being the available end-to-end capacity.

At the institute we are designing a swift measurement methodology for indoor benchmarking with the aspects of temporal and spatial effects in mind. Furthermore, to increase measurement speed and make this measurement possible, we have applied a modified version of the packet pattern method introduced in the resourceful probing section.

The new measurement methodology that allows for swift and repeatable measurements of the mean network performance by combining three techniques: Firstly, the instantaneous IP throughput is derived within one second by using a novel packet pattern method and an Android cellphone with an external antenna. Secondly, the long-term trend in the IP performance, that is the slowly changing average network load, is removed. Thirdly, the scenario mean of the remaining small-scale fading scenario with overlaid fast network fluctuations is obtained by statistical inference, namely, spatial systematic-sampling with an XY-positioning table. Currently we approach to extend the method towards drone based measurements with machine learning control.

Optimizing Hybrid Network Access Technologies

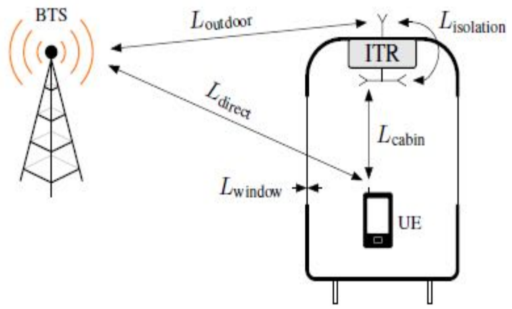
Hybrid internet access allows combining different access technologies to be mapped into a single connection from the user point of view. Current solutions are splitting up the traffic flow at the packet level and distribute the packets mong the available interfaces. he split is done by a central box acting as a trafficcombiner. The distribution of packets is a challenging task if there is a strong asymmetry in the link capacity, the transportation delay, and the packet loss rate, e.g., a packet loss on the underlying IP link can stall the TCP flow on both links. In this activity, we defined a structured test procedure that allows comparing the user performance of different solution and levels of implementation of hybrid access.



Hybrid Network Access Technologies.

We defined and created different physical scenarios of hybrid internet access technologies regarding bandwidth, loss, and delay. On the base of this, a set of KPIs is identified, and a first measurement campaign is performed to extract the delay and loss profile in standard LTE cells. In the first evaluation, we analyzed the existing solutions for their performance. This allows developing systematic optimization strategies for the algorithms in use.

Measurement Based Modelling of In-Train Repeater Deployments



Holistic in-train repeater model.

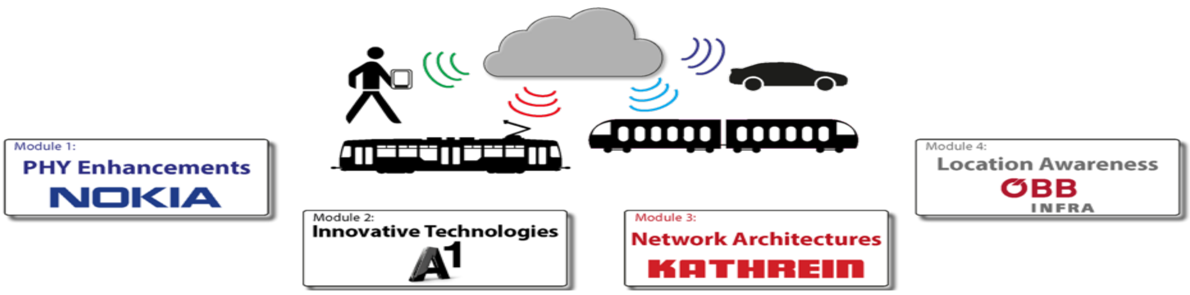
In recent years, the demand of train-commuting nomadic users for the Internet has been a huge challenge for train and mobile operators. Consequently, train operators have started to deploy in-train repeater systems to increase mobile users'service quality.
These systems generally follow the structure of static deployments. However, in contrast to a static deployment where the system is set up once using constant parameters that are based on an initial measurement, the train will commute in dense urban city centers and sparsely populated rural areas.
We work on a holistic model that helps to understand the role of each system component, namely, cabin pathloss, repeater model, window penetration loss, and outdoor pathloss, in which each individual element can be measured independently. The model is parametrized by measuring an existing in-train repeater deployment of a high-speed trai in cooperation with the national Austrian railway company.

1.4 Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion

The aim of the Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion is to enhance the dependability (reliability and timeliness) of wireless communications even at high mobility, such as to support applications that require beyond best-effort services, e.g., road-safety applications, augmented and virtual reality, UAV control and communication. Our main focus thereby is on 5G and beyond mobile communication technologies. The CD-lab started its research work in 2016 and has currently twenty members, seven of which are PhD students.

The CD-Lab is composed of four research modules: PHY Enhancements, Innovative Technologies, Network Architectures and Location Awareness, where we actively collaborate with our four industrial partners Nokia, A1, Kathrein and ÖBB Infra.

The focus of Research Module 1 PHY Enhancements is on the optimization of orthogonal and non-orthogonal multicarrier transmissions and on full-dimension (distributed) massive MIMO transmissions. Within Research Module 2 Innovative Technologies, we investigate transmissions in the millimeter-wave band and cellular-assisted vehicular communications based on non-orthogonal multiple access. In Research Module 3 Network Architectures, we conduct system level investigations and optimizations of large-scale wireless networks and in Research Module 4 Location Awareness, we investigate machine learning based techniques for user location and the potential of exploiting location awareness for self-organizing networks. Our research work spans multiple layers, ranging from measurement based channel characterizations over link level signal processing to system level analysis and optimization.



Structure and research focus of the CD-lab.

2. Communication Networks

The communication networks group research focus is security in communication networks and critical infrastructures, such as the electricity grid.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. The communication networks group works on network supervision and network protection methods, anomaly detection techniques and mitigation strategies.
Within this area the group works on the following topics:

2.1 Malware Communication

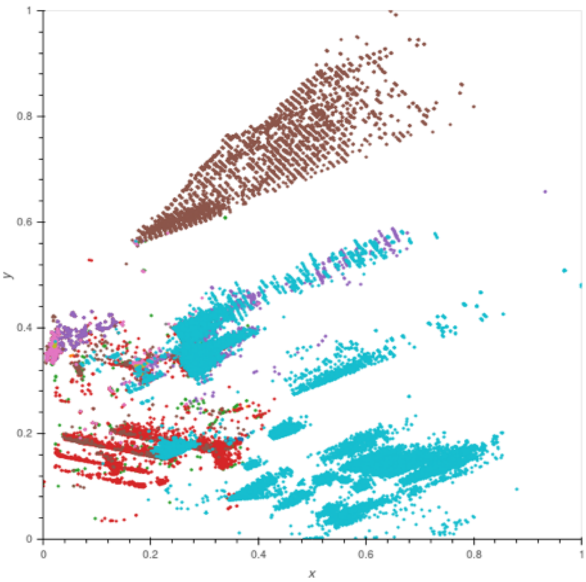
The protection of communication networks against new and unexpected attacks remains a challenging task. Due to the large amount of software vulnerabilities or even opportunities to alter hardware, the spreading of malware is hard to prevent. Nevertheless, sophisticated malware needs to communicate in order to spread to further devices or networks, to exfiltrate information from compromised machines or to establish and operate command and control structures to control large scale attacks.

Such malware communication becomes more and more sophisticated, using encryption, obfuscation and covert data exchange techniques to hide in normal network traffic.

The communication networks group investigates what approaches can be used to hide data exchanges in normal traffic and develops methods to detect malware communication in communication networks and critical infrastructures.

In the area of hiding techniques, the group works on network steganography methods to establish covert channels and the use of high-speed digital signatures to transmit information in subliminal channels.

On the detection side, the group investigates botnet communication patterns, malware spreading methods and the detection of malware communication in encrypted traffic. For the detection of suspicious traffic, the group uses statistical methods, machine learning, clustering and different anomaly and outlier detection methods. Challenges are the high volume and dynamics of streaming network data, the evolution of attack techniques and the accessibility of features in encrypted traffic. One method to improve machine learning performance is the preprocessing and reduction of input features. The CN group works on methods to assess the quality of different input features and on the aggregation and preprocessing of features in order to reduce the dimensions provide as input for the decision process.



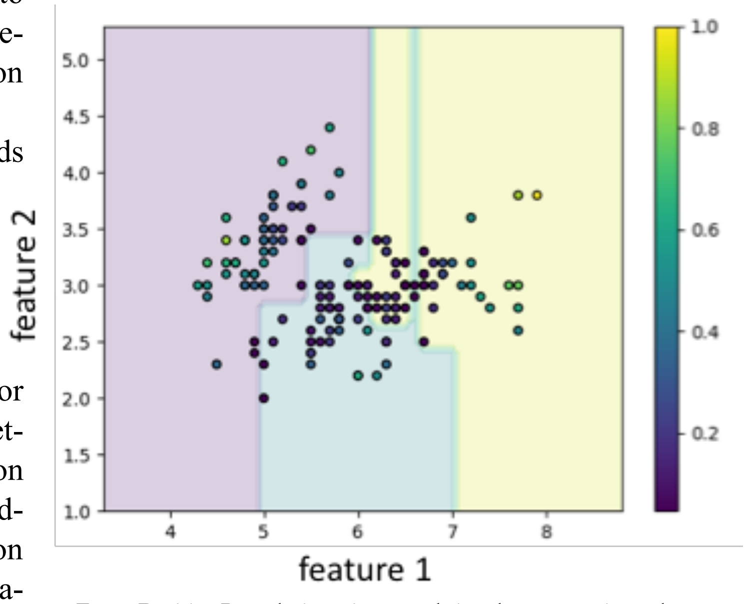
Detection of malware communication based on a feature vector that has been reduced to two dimensions.

2.2 Robust Anomaly Detection Methods

Besides standard statistical analysis, machine learning methods provide sophisticated tools to detect suspicious anomalies in classical network traffic. Nevertheless, in contrast to other machine learning settings in network security we have to deal with active adversaries that try to prevent detection and circumvent detection algorithms.

That means that our detection methods need to be robust in adversarial settings. The research area of adversarial machine learning deals with methods to harden algorithms against adversarial attacks on input features or algorithms.

The CN group examines possibilities for the creation of adversarial samples in network traffic, works on robust detection methods to protect algorithms against adversaries by defining fuzzy decision boundaries and investigates the transferability of adversarial activities to different machine learning methods.



Fuzzy Decision Boundaries to increase their robustness against adversarial samples. Dot colors are derived from distances to the thresholds.

2.3 Components for Secure Communication in Critical Infrastructures

Critical Infrastructures such as the electricity grid are essential for the functioning of a modern society and therefore tempting targets for highly skilled attackers. Such infrastructures nowadays require more and more communication technology in order collect sensor data and distribute commands in order to control their dynamic behavior.

As a consequence, communication networks for critical Infrastructures have high security demands. Interfering with supervision and control functions in cyberspace can influence real world physical systems, and deactivate or damage critical infrastructure components. In order to secure critical infrastructure communication, the CN group works on secure methods for sensor data collection (e.g., for wide area monitoring in smart grids), secure clock synchronization, which is essential for timely sensor data analysis, and the assessment of suitable digital signature methods to work in high speed environments. Furthermore, the group investigates malware spreading patterns and the detection of suspicious traffic in critical infrastructure communication.

Together with the Institute of Energy Systems and Electrical Drives (ESEA), the CN group established the FUSE Testbed (Future Self-Organizing Energy Networks) at TU Wien that allows experiments and the collection of data for research in smart power grids.

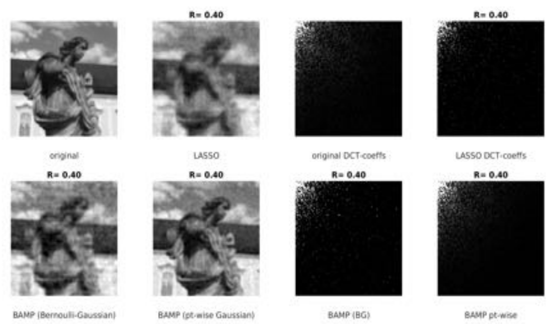
3. Multimedia Systems

Research in this field involves signal processing for multimedia applications, compressed sensing in particular, for applications ranging from image processing to wireless communications. The goal is to optimize the overall system performance while efficient use is made of the system resources available.

3.1 Compressed Sensing and Iterative Recovery

Compressed sensing is about sampling signals at a sampling rate far below the classical sampling theorem; perfect (or at least very high quality) recovery is still possible when there is sufficient structure (such as “sparsity”) in the signal. In practical applications (such as MRI scanners) the vector dimension of the signals can be very large (100000 and more), so extremely efficient recovery algorithms are crucial as well as good dictionaries to perform the sampling process, the latter being a multiplication of the signal vector with a measurement matrix (the dictionary).

We work on fast recovery of very high-dimensional signals with different types of “structure” by iterative algorithms, in particular Bayesian Approximate Message Passing (BAMP), to solve problems in image processing (e.g., single pixel imaging) but also in communications (e.g., sparse regression codes, detection of RFID tags). The Bayesian framework allows to go beyond classical compressed sensing, because not only “sparsity” of the source signal can be exploited but rather the full probability density function of the signal vector (even in a multidimensional setting), which allows for much better reconstruction quality (at much lower complexity) than the classical approach by L1-minimization (LASSO). An example is the detection of radio-frequency identification tags: the classical problem of “collisions” is re-interpreted as a compressed sensing measurement, and the application of BAMP allows to detect a sparse selection of RFID tags form a huge list that in fact forms the compressed sensing measurement matrix. A second example is single-pixel imaging. It is attractive for applications such as THz or infrared imaging, where large arrays of parallel sensors (which are used in conventional digital cameras) cannot be realized. The basic idea is to repeatedly take (single-pixel) measurements of the accumulated electromagnetic wave intensity emitted from randomly chosen parts (pixels) of the imaging object. Image recovery from those linear, randomly chosen measurements can be written as a compressed sensing problem, and, if the image contains structured objects, its accurate reconstruction will be possible, even if the number of measurements is much lower than the number of image pixels to be recovered. Classical compressed sensing recovery relies on the sparsity of the signal, and for images sparsity is observed when the image is represented by DCT (discrete cosine transform) coefficients. The DCT coefficients are, however, not only sparse, but it is also known which of the coefficients tend to take large and small values, and one can also measure the probability density functions of the DCT coefficients and exploit this point-wise prior knowledge in a newly developed BAMP scheme.



3.2 Machine Learning

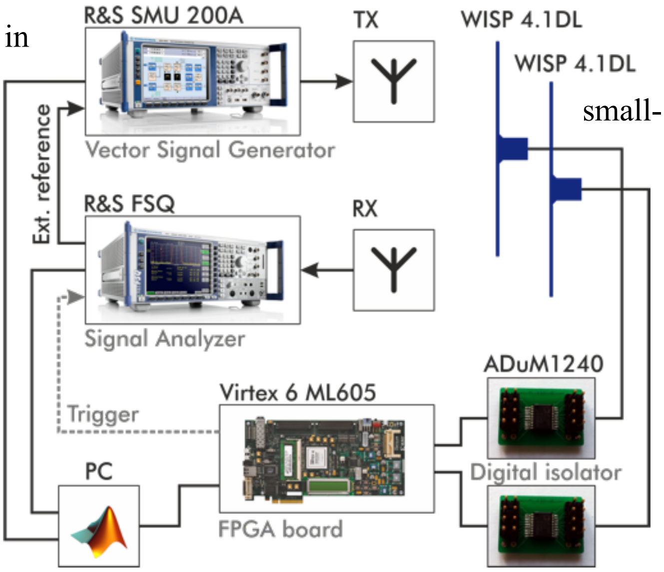
While classical CS exploits sparsity to actively compress the observed signals, one can also use the raw data directly for extracting the inherent structure to obtain a sparse model for the observed data. This can be cast as an (unsupervised) machine learning problem based on unlabeled data. In particular, we focus on two specific machine learning methods:

Dictionary Learning: the idea is to represent the observed signals as sparse linear combinations of a single underlying dictionary. Thus, a sort of analog sparse source coding is performed, with the dictionary representing the source code. The problem is that the underlying dictionary is unknown and has to be determined based on the data. We investigate fundamental limits on how accurately this is possible.

Sparse Graphical Models: A popular way of representing complex systems with a large number of components (nodes) and complicated interactions between them are graphical models. If we assume that the observed data are realizations of a random vector with a fixed probability distribution, the problem of graphical model selection is to determine the underlying graphical model. In particular, we are interested in the conditional independence graph (CIG) of a random process. Two nodes of a CIG are connected if the corresponding random variables are conditionally dependent, given the remaining variables.

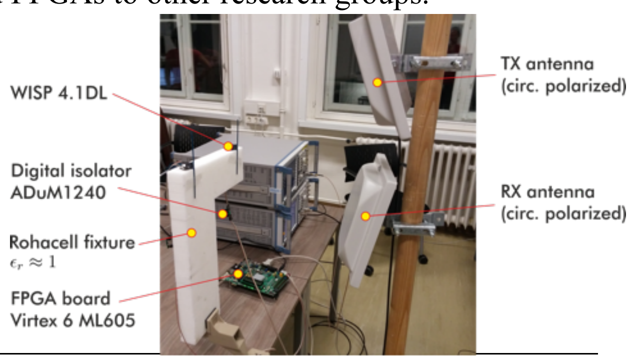
3.3 Channel Coding

Error-correction channel coding has a key role in digital communication systems. Due to delay constraints of the applications, codes with small-to-medium block size are of particular interest. A special problem, which is very important in practice, is the realization of a flexible "adjustable" code rate, as the time-variant fading channels necessarily require adaptive modulation and coding. We investigate Sparse Regression Codes that are specifically constructed for those situations. Those are linearly superimposed Gaussian vectors that are selected by the data bits from a large codebook, and decoding is conducted by Approximate Message Passing, as decoding can be cast as a compressed sensing recovery problem.



Programmable Hardware

We implemented the algorithms investigated for detection of RFID tags in programmable hardware (Field-Programmable Gate Arrays, FPGAs) to obtain real results with commercially available RFID hardware. 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.

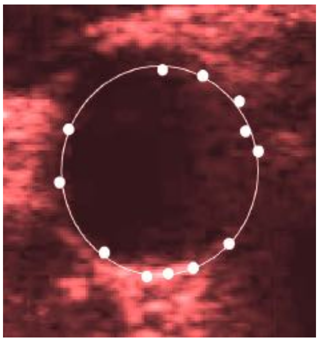


4. Signal Processing

Major directions and applications of our recent signal processing research include statistical signal processing, sensor networks, multiobject tracking, 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") and under grant "Random Finite Set Methods for Network-Based Estimation," by the Vienna Science and Technology Fund (WWTF) under grant NOWIRE ("Noncoherent Wireless Communications over Doubly Selective Channels"), and by the Czech Science Foundation (GACR) under Grant "Sequential Bayesian Estimation of Arterial Wall Motion."

4.1 Statistical Signal Processing

We developed a "single most likely replacement" type method for blind sparsity-exploiting deconvolution. This method exploits a constraint on the temporal or spatial distance of consecutive signal components for a reduction of complexity. 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. Furthermore, 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 approximate marginalization of distributions with a general factor structure.



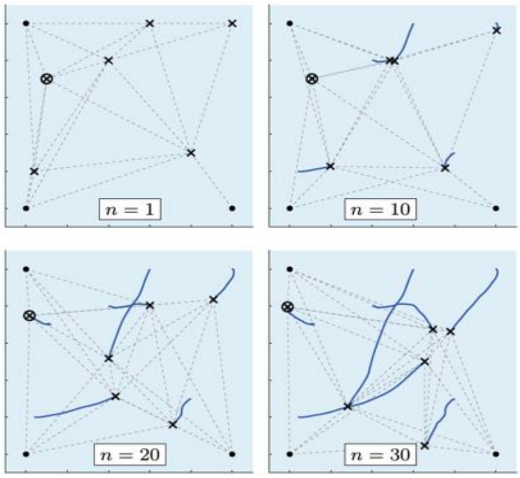
Measured ultrasound image showing a cross section of the carotid artery. The artery is represented by a circle, and the time-varying circle radius is estimated by detecting and tracking points representing strong scatterers in the ultrasound image.

More on the theoretical side, we investigated minimum variance estimation of sparse vectors using the mathematical framework of reproducing kernel Hilbert spaces. Here, our focus was on closed-form characterizations of the locally minimum variance estimator and its performance. We also introduced a definition of entropy for singular random variables and used this definition to study source coding for singular random variables. We applied our methods to multipath component estimation, to wave estimation in electrocardiography, and to the tracking of the movement of the carotid artery based on ultrasound video sequences.

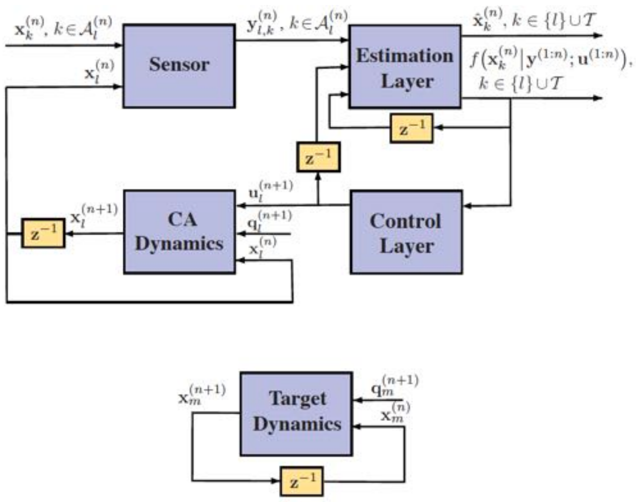
4.2 Sensor Networks

In the area of statistical signal processing for wireless sensor networks, we emphasize a fully distributed (decentralized, cooperative) approach that does not require a fusion center. Our goal has been to estimate global or local states using only local processing at the individual sensor nodes and local 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.



Example of a decentralized sensor network comprising fixed and mobile network nodes. The locations and trajectories of the mobile network nodes are shown at four different times. The dahed lines indicate the pairs of nodes that are able to measure their distances and to communicate at the respective time.



Block diagram of a combined estimation-control system for tracking a moving object using mobile cooperative agents (CAs). The motion of the CAs is controlled such that the measurements provided by the CAs are maximally informative about the unknown object state to be estimated.

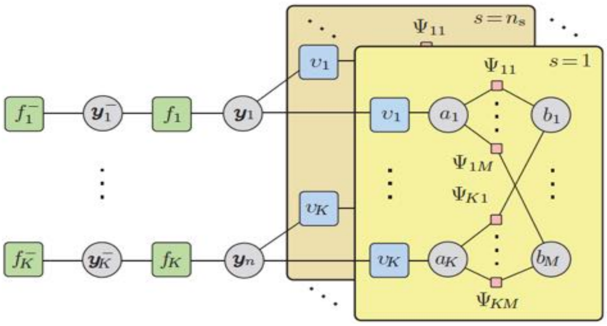
We also devised distributed estimation methods based on factor graphs and the belief propagation algorithm. We were able to integrate noncooperative network nodes (e.g., moving objects not communicating with the sensor nodes) by combining belief propagation with a consensus scheme. Using the belief propagation approach, we devised distributed algorithms for cooperative simultaneous localization and tracking and cooperative simultaneous localization and synchronization.

Further results in the field of sensor networks include distributed particle filtering methods for correlated sensor measurements and for asynchronous sensor networks. We also developed a belief propagation- and consensus-based method combining distributed sensor localization with distributed sensor control. Finally, we used the likelihood consensus scheme for distributed tracking in the presence of clutter and missed detections, and for objects whose presence is uncertain.

4.3 Multiobject Tracking

Multiobject tracking aims at estimating the states—i.e., positions and possibly further parameters—of moving objects over time, based on measurements provided by sensing devices such as radar, sonar, or cameras. The number of the objects is usually unknown. In addition, also the association between measurements and objects is unknown, and it is possible that certain measurements do not originate from objects and certain objects do not lead to measurements.

Our main contribution has been the introduction of factor graphs and the belief propagation algorithm to the field of multiobject tracking. The belief propagation approach allows an efficient solution of the measurement–object association problem. Moreover, the complexity of the resulting multiobject tracking algorithms scales very well in all relevant system parameters. Finally, the belief propagation-based design of multiobject tracking algorithms features a desirable versatility, modularity, and intuitiveness. Our belief propagation-based multiobject tracking algorithms are able to fuse the measurements of multiple sensors, and to continually adapt to time-varying system parameters.



Elementary section of a factor graph for multiobject tracking using the measurements provided by multiple sensors. This factor graph enables the use of the belief propagation algorithm for efficient multiobject tracking and measurement-object association. Each yellow box corresponds to one of the sensors.

We also devised multiobject tracking algorithms in which the object states and the measurements are modeled by finite point processes and, partly, marked finite point processes. The use of marked finite point processes enables the estimation of entire object trajectories with consistent identification of the objects.

4.4 Wireless Communications

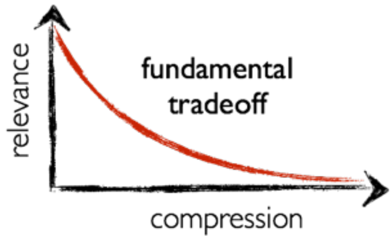
Our recent contributions to the area of wireless communications include receiver algorithms for communication over doubly selective and frequency-selective channels and information-theoretic performance bounds.

For multiuser communication systems employing multiple-antenna multicarrier (MIMO-OFDM) transmission and interleave division multiple access (IDMA), we devised iterative receivers based on 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 a "turbo-style" architecture. The consistent integration of channel estimation in the iteration loop was observed to yield substantial performance gains.

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, and likelihood ascent search.

We used information-theoretic methods to investigate the number of degrees of freedom (capacity pre-log) of MIMO non-constant block-fading 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 model. Furthermore, we studied lossy source coding for finite point processes. We developed a rate-distortion theory for finite point processes and derived lower and upper bounds on the rate-distortion function.

5. Communication Theory



Our activities deal with the physical layer of wireless networks, information theory, and (distributed) algorithms on graphs and networks. Our research has been funded by the Viennese Science and Technology Fund (WWTF) via the projects

- *The Information Bottleneck Principle in Multiterminal Communication and Inference (TINCOIN)*
- *Communication and Complexity Constrained Inference over Graphs for Big Data (Co3-iGraB)*
- *Unleashing finite-alphabet implementations of LDPC decoders (UNFOLD)*

and by the European Union via the FP7 projects

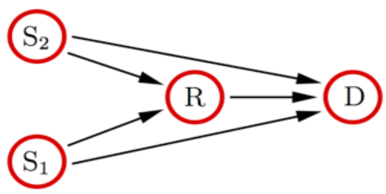
- *Enhanced Interference Alignment Techniques for Unprecedented Spectral Efficiency* (HIATUS)
- *Network of Excellence in Wireless Communications#* (NEWCOM#).

5.1 Multiterminal Communication

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 parallel interference-free transmissions within the same spectrum. 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 has resulted in a patent application with *Ericsson* (Sweden).

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 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 to multiway relay channels.

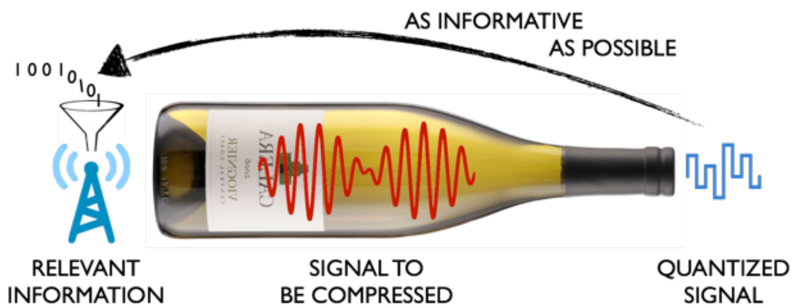
Decode-and-forward is an alternative relaying strategy in which the source data is decoded and re-encoded (possibly in combination with a network code) at the relay. In a collaboration with Chalmers University we have studied decode-and-forward in the multiple access relay channel for the case where the data of the sources is correlated. Specifically, we proposed a scheme that is based on bilayer spatially coupled low-density parity check 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 approaches the Shannon limit.

5.2 Information Bottleneck

A lot of our efforts were dedicated to further the theoretical foundations and applications of the so-called information bottleneck (IB) method. The IB is a scheme that aims for maximal data compression/clustering while p reserving the maximum amount of relevant information. For the practically extremely important special case where the quantities involved have Gaussian distribution, we derived closed-form expressions for the rate-information function that characterizes the compression/ relevance trade-off and we investigated the similarities and differences to rate-distortion compression with squared-error. Furthermore, we gave a Shannon-theoretic foundation for the operational interpretation of the Gaussian IB. We also considered IB-optimal quantization of log-likelihood ratios (LLRs) and derived an efficient algorithm for the design of LLR quantizers based either on the unconditional LLR distribution or on LLR samples.



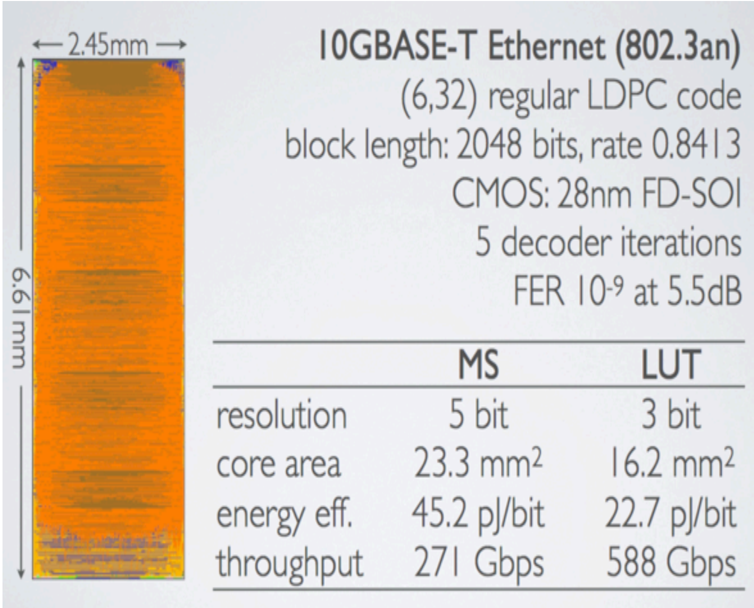
The IB can be thought of as a source coding method for a single source. Building on this interpretation, we collaborated with *CentraleSupélec* (France) in a Shannon-theoretic study of novel multi-terminal source coding problems motivated by biclustering applications. Here, the encoders aim for rate-limited encodings of multiple sources such that their mutual information is maximized. We derived bounds on the achievable rate-information region for this problem and we established connections with hypothesis testing, pattern recognition, and multiple-description versions of the CEO problem.

5.3 Transceiver Design

We have applied the insights gained from the investigation of the IB in a number of transceiver design tasks.

We studied the maximum rate achievable over a Gaussian channel with Gaussian input under channel output compression. This problem is relevant to receive signal quantization in practical communication systems. We used the Gaussian information bottleneck to provide closed-form expressions for the rate-information function, which quantifies the optimal trade-off between the compression rate and the corresponding end-to-end capacity. We furthermore showed that mean-square error optimal compression of the channel output preceded by a particular linear filter achieves the optimal trade-off, thereby greatly facilitating the design of channel output quantizers.

In collaboration with *Universitat Politècnica de València* (Spain), we further investigated information-optimal compression of channel outputs and LLRs in the context of next-generation digital television. To combat small-scale fading, these systems use long time-(de)interleavers (TDIL) that require large amounts of memory. Quantization prior to TDIL bears the potential to reduce the receiver complexity significantly. We derived non-uniform quantizers for the I/Q components as well as the LLRs that are optimal in the sense of maximum BICM capacity. Using simulations with a real mobile scenario, we found that our schemes are capable of reducing the receiver quantization resolution (and hence the memory requirements) by up to 58.3% compared to the state of the art.



Chip layout for a 588Gbps LDPC decoder designed for 10GBASE-T Ethernet using the UNFOLD software framework and performance comparison with MS decoder.

Finally, we investigated communication schemes with feedback. The well-known Schalkwijk-Kailath scheme has the drawback of requiring perfect feedback. We derived expressions for achievable rates and error probabilities for linear transmission schemes over Gaussian channels with rate-information-optimal quantized feedback. We later extended our approach to the Gaussian multiple access channel with feedback and to the Gaussian broadcast channel with feedback. For these multi-user scenarios, we introduced a superposition scheme that splits the transmit power between an Ozarow-like linear-feedback code and a conventional code that ignores the feedback. The associated sum rate was maximized using difference of convex functions optimization tools. In our most recent work, we studied these approaches in the practically more relevant non-asymptotic (finite block-length) regime and devised corresponding optimal resource allocation schemes.

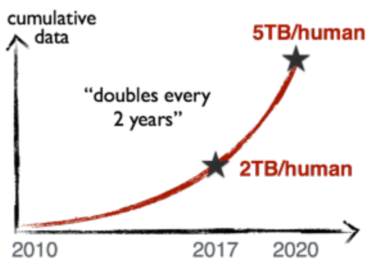
5.4 LDPC Decoders

In collaboration with *Ecole Fédérale de Lausanne* (EPFL, Switzerland), we proposed a novel algorithm for decoding (regular) low-density parity-check (LDPC) codes. Our decoder uses message quantization and replaces the update rules of the belief-propagation and min-sum (MS) algorithms with a look-up table (LUT) that is designed to maximize the mutual information between the decoder messages and the code bits. Even with very small message alphabets, the proposed algorithm can achieve better error rates than a floating-point min-sum decoder. The decoder iterations were later unrolled into dedicated hardware stages and the ideas were extended to irregular LDPC codes. As a result, we could propose an LDPC decoder with an unrolled full-parallel hardware architecture. The decoder benefits from a serial message transfer approach between the decoding stages to alleviate the well-known routing congestion problem in parallel LDPC decoders. The finite-alphabet message passing algorithm resulted in an architecture with reduced bit-width messages, leading to a significantly higher decoding throughout and to a lower area compared to a min-sum decoder when serial message-transfer is used. Finally, the architecture was placed and routed, with postlayout results showing that the finite-alphabet decoder with the serial message-transfer architecture achieves an unprecedented throughout of 588 Gbps with an area of 16.2 mm^2 and dissipates an average power of 22.7 pJ per decoding bit in a 28 nm CMOS library. Compared to the reference design, this corresponds to an improvement of area and power efficiency by factors of 3.3 and 2, respectively.

In follow-up work, we developed a powerful but easy-to-use software (C++/Matlab/VHDL) framework for the design, implementation, and testing of LUT decoders. The software can be obtained via the UNFOLD project website https://www.nt.tuwien.ac.at/UNFOLD which provides brief background information, a short description of the software, and a design flow example (the software is provided under the terms of a GNU General Public License).

5.5 Graph Signal Processing

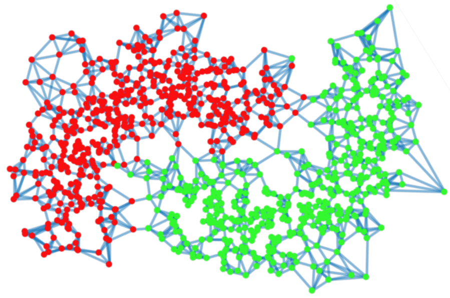
The most recent line of work deals with (statistical) inference in huge digital data sets as encountered e.g. in sensor networks, social networks, customer databases, biological networks, etc. Graph signal processing is a new and exciting scientific paradigm in which structured data is modelled as a graph signal, i.e., as labels (often numerical values) on the nodes of a graph, whose edges capture some form of interdependence of the nodes.



A key problem in this area is the reconstruction of a graph signal from a small number of measured samples. We devised a powerful approach for solving this problem by capturing the signal's smoothness in terms of its total variation and by formulating the recovery task as an optimization problem. We developed a toolbox of algorithms to solve this optimization problem as efficiently as possible depending on the topology of the underlying graph. Further numerical experiments were conducted to assess the performance of our methods. With both synthetic data and a real-world dataset (Amazon co-purchases) we observed that our scheme outperforms existing state-of-the art schemes in terms of recovery accuracy and computational complexity.

Another major activity dealt with the problem of learning the topology of a graph model from given data. Following similar reasoning as with graph signal recovery, we imposed that the data be smooth with respect to the graph to be found. This leads to an optimization problem for the graph's edge weights, which can flexibly be augmented with side-constraints that capture the specific properties of the application at hand. We proposed to solve the weight optimization problem using a variant of the ADMM algorithm. We then extended this approach to the case of missing and imperfect training data, leading to a combination of the learning scheme with our previously developed signal recovery method. Numerical experiments with data on the voting behaviour of Austrian *Members of Parliament* (MP) and with images demonstrated the superiority of our method over state-of-the-art graph learning algorithms. More specifically, we successfully demonstrated the learning algorithm on a data set consisting of yes/no votes of the 183 Austrian Members of Parliament (from https://politometer.addendum.org) using a single parliamentary sitting with 75 votes and an average voter participation of 72% our method was able to perfectly recover the parliamentary group affiliation of all MPs, and as a side-product, to predict the votes missing due to absence of MPs.

Finally, we considered the problem of graph clustering, i.e., portioning a graph into disjoint subgraphs (clusters) by appropriately labelling the graph nodes. By advocating the use of signed graphs to capture the dissimilarity of certain nodes, we augmented spectral clustering methods and total variation based schemes and thereby were able to achieve substantial improvements in clustering performance.



6. Robust and Reliable Communication

Nowadays the penetration of our daily life with communication systems is extremely high. They are mobile in nature to support the nomadic behavior of human beings. We want to communicate at any location, all the time and with best quality at low costs. Due to the many active communication systems we have to expect unpredictable types of interference. Due to the limited bandwidth and the many active communication-systems a possibility of conflicts between communication systems in unavoidable. In the past the communication engineers have put much effort to predict the interference (channel state) as accurate as possible. The problems with prediction are well known (error in the estimate, time consuming, power consuming, complex algorithms, problems with the stability of algorithms). If we know exact and in advance the channel state we 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 with 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 structures). Sources of interference range in the time-domain from permanently present to pulsed interference. In the frequency-domain we encounter narrowband and broadband interference. Narrowband interference is represented with continuous wave interference. Sources of interference range from single-path 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 a 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. The movement from a well defined interference environment to a roughly unknown interference environment needs a blind detection concept. 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). The solution proposed in this project is to focus on simple interference reduction algorithms which make no (less) assumptions about the interference type, composition and offers a great improvement in performance. A promising concept for this task is to use adaptive nonlinearities driven by threshold crossing information, which is simple, fast and derived inline. This solution method fits to the assumptions made above.

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.

7. Flexible Wireless Systems

7.1 Celluar Communications and Ultrawideband Radio

Our present converged 4G networks enable efficient transmission and distribution of digital content: The Internet is available in the mobile domain and allows the generation, transmission, distribution, storage, and manipulation of information. Wireless technologies now need to „grow up“ and become dependable. The challenge is to extend the mobile Internet to production, transportation, distribution, storage, and manipulation of real-world objects ("internet of things"). 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 Multiple-Input Mulitple-Output (MIMO) transmission using antenna array technology is now the commercial baseline in Wi-Fi and mobile networks. The current trend towards *massive MIMO* in Time Division Duplex (TDD) mode progresses steadily from LTE-Advanced towards 5G.

Wireless networking of sensors and instrumentation enables new application fields: Intelligent Transport, Smart Metering, Intelligent Production, etc. We investigate dynamic resource allocation schemes and interference mitigation 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 5G networks based on software-defined radio (SDR) concepts.

Peer-to-peer and ad-hoc networks based on direct radio communication between mobile entities is necessary for the internet of things. Traffic telematics applications are 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. Advanced active safety is the next step in intelligent transport and this requires dependable networking.

Nonlinear detection techniques offer resource efficient solutions in communication systems. Low complexity digital receiver designs suffer from the capture effect in strong non-Gaussian interference. We combat the capture effect with an adaptive nonlinearity in the receiver prior to detection. The interaction between the fast self-adapting nonlinearity and a masking digital matched filter allows to mitigate both Gaussian and non-Gaussian interference.

The family ultra-wideband (UWB) transmission techniques is especially suited for communication among electronic sensors and actuators over short ranges. They cause little interference to existing narrowband systems. In many application scenarios for the Internet of Things, the spectral efficiency of the transmission technology is of less importance than its power efficiency. UWB transmission can also be incorporated into passive tags which use backscatter communication. Key applications will be low-power sensor networks and robust embedded systems which require neither batteries, nor external antennas. Thus, UWB transmission enables the association of data with objects and their location: A key to the Internet of Things.

7.2 Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility

The Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility started in 2009 and was phased out after its very successful seven years lifetime in 2016. The lab focused 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 avoided simplistic assumptions on the communication channel statistics. We evaluated our designs on testbeds comprising real-world wireless communication environments. Thereby, we validated 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 achieved through multiple antenna transmission and reception.

Our research plan consisted of five modules: Vehicular Connectivity (Module 1 with Kapsch TrafficCom AG), Smart Tags for Sensor Nets (Module 2 with Infineon Technologies Austria AG), Mobile Communications Evolution (Module 3 with A1 Telekom Austria AG and Kathrein Austria GmbH), and Nearfield Power Efficiency (Module 4 with NXP Semiconductors Austria GmbH). The research in Module 1 focused on reliable real-time wireless technologies in time-variant communication scenarios for safety-related applications. In Module 2, we investigated advanced transmission techniques for low energy consumption tags and increased the robustness of transmission in industrial environments. In Module 3, we measured and optimized multiuser throughput of multi-antenna transmission under delay constraints on the wireless channel and the novel inter-base station co-operative signaling.

Further, we evaluated the gain from interference management for 4G LTE based on orthogonal frequency division multiple access (OFDMA). Efficient energy and data transmission for contactless identification was the central challenge in Modul 4. In 2013, the fifth module was started with the partners PIDSO Propagation Ideas and Solutions GmbH and BMW Research and Technology GmbH. In Module 5, the electro-magnetic charac-teristics of carbon fiber reinforced composite materials were investigated, as they are in use for ultralight vehicular chassis for electro-mobility. Based in these results, multiple antennas for intelligent transport systems in electrical vehicles were desgined, optimized, and characterized. Since 2017, the newly founded Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion carries out research on fifth generation (5G) wireless networks at the institute