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MASCOT

Multiple-Access Space-Time Coding Testbed

Specific Targeted Research Project

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Final Activity Report

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Christoph Mecklenbräuker, Sue Ivan
ftw. Telecommunications Research Centre Vienna

Revision 2

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Executive Summary

The *Multiple Access Space-Time Coding Testbed* project (MASCOT) is a three year project which started in January 2006. The project is carried out by eight partners: ftw. Forschungszentrum Telekommunikation Wien Betriebs-GmbH (Co-ordinator), Nokia Corporation, Fraunhofer Institute for Telecommunications Heinrich-Hertz-Institut, Politecnico di Torino, Vienna University of Technology, Eidgenössische Technische Hochschule Zürich, Fundació Barcelona Media Universitat Pompeu Fabra, and Università della Calabria. The contributions of MASCOT are organised into three workpackages:



WP1: Baseband transceiver algorithms, space-time code design, and system-level aspects. This workpackage is devoted to developing robust (with respect to propagation conditions) space-time codes and corresponding low-complexity decoders, MIMO-OFDM channel estimators, and algorithms for link adaptation, retransmission, and scheduling which are suitable for Multiuser Multiple-Input Multiple Output (MU-MIMO) systems. Here, particular attention is given to hardware implementation and complexity constraints.

WP2: VHDL reference designs of selected key algorithms and testbed implementations. The most promising algorithms will be implemented in hardware and tested on ETHZs real-time MU-MIMO testbed. One of the key deliverables of the project will be a library of VHDL reference designs of algorithms for MU-MIMO systems. This library may be made available to the European industry for commercial licensing subject to mutually acceptable agreement thereon between the MASCOT partners.

WP3: Performance limits and tradeoffs. Understanding of the performance limitations and tradeoffs in MU-MIMO systems is still patchy. We therefore plan to investigate information-theoretic performance limits of MU-MIMO systems under realistic propagation conditions. We will

also study the tradeoffs between different MIMO gains in the multi-user context. This will provide us with insights into problems related to system design.

WP4: Dissemination and exploitation. These activities constitute an important part of the project. These efforts include scientific publication of project results; creation of a public web site; contributions to relevant standardisation efforts; organisation of tutorials/industry courses and *open house events*; patent applications; and offering VHDL reference designs for commercial licensing.

During the third reporting period (01.01.2008—28.02.2009), the research in WP1 focused on MU-MIMO resource allocation and proportionally fair schedulers, as well as computationally efficient algorithms for detection and precoding. MU-MIMO space-time codes for multiple access were developed. A key result from WP1 are the baseband algorithms summarized in deliverable D1.3.2, some of which have been made available as a VHDL reference design. WP2 focused on the reference designs and the MU-MIMO OFDM testbed. The key result from WP2 is the VHDL Library of Reference Designs which is made available as deliverable D2.2.1 The research in WP3 focused mainly on multiuser capacity and quality-of-service regions, and scheduling concepts for relay networks equipped with multiple antenna arrays. A key insight from WP3 is that every comprehensive capacity region can be expressed as a sub-level set of an interference function. This facilitates a general framework for analyzing performance trade-offs in multiuser networks.

One special session was organised at EUSIPCO 2008 on “Complexity Reduction in Multiuser MIMO Systems,” and a special issue for the IEEE Journal on Selected Topics in Signal Processing (JSTSP), on *Managing Complexity in Multiuser MIMO Systems* with several contributions from MAS-COT is in preparation for publication during 2009. The second industry course and the second ETHZ Open House Event were held in February 2009.

In total, more than eighty contributions to journals and conferences were submitted in 2008–2009.

Further information about the project’s goals and results along with announcements of major MAS-COT-related events are available at the following web-site: <http://www.ist-mascot.org>

Chapter 1

Project objectives and major achievements during the reporting period

During 2008, MIMO technology is being researched in several US-based (Intel, Freescale, Alcatel-Lucent, Bicin), European (France Telecom, Nokia, Nokia Siemens Networks, ST Microelectronics), and Far East-based (Mitsubishi Electric, NTT DoCoMo, Samsung, Huawei) industrial companies.

MIMO technology drivers in Europe are 3GPP Long Term Evolution (LTE), MIMO-enhanced Wireless LAN (IEEE 802.11n), and mobile WiMax systems according to IEEE 802.16e/m. These three systems use MIMO combined with variants of Orthogonal Frequency Division Modulation (OFDM). Research in the MIMO area focused almost exclusively on single-user point-to-point links. Very little is known about MIMO communications in cellular (multi-user) and ad-hoc network contexts.

Recent scientific advances in multi-user MIMO coding and the associated advanced radio resource management have not yet been adopted by industry. The MASCOT project allows Europe to lead this important research and development area. The goal of the MASCOT project is to address fundamental issues of MU-MIMO systems. Rather than focusing exclusively on a single standard, we work on challenges which are generic to MU-MIMO systems. In order to fuel MIMO research in European companies, we developed VHDL reference designs for the key transceiver algorithms for MU-MIMO systems. This library is made available to companies and universities for licensing. The real-time MU-MIMO testbed at ETHZ is the platform for implementing and testing the algorithms developed in the course of MASCOT under real-world conditions.

This Periodic Activity Report reviews the third reporting period of the

MASCOT project (1.1.2008—31.12.2008).

1. During 2008–2009, the research in WP1 focused on MU-MIMO resource allocation and proportionally fair schedulers, as well as computationally efficient algorithms for detection and precoding. MU-MIMO space-time codes for multiple access were developed. A key result from WP1 are the baseband algorithms summarized in deliverable D1.3.2, some of which have been made available as a VHDL reference design.
2. WP2 focused on the reference designs and the MU-MIMO OFDM testbed. The key result from WP2 is the VHDL Library of Reference Designs which is made available as deliverable D2.2.1
3. The research in WP3 focused mainly on multiuser capacity and quality-of-service regions, and scheduling concepts for relay networks equipped with multiple antenna arrays. A key insight from WP3 is that every comprehensive capacity region can be expressed as a sub-level set of an interference function. This facilitates a general framework for analyzing performance trade-offs in multiuser networks.

Chapter 2

Workpackage progress of the period

The progress in the workpackages was monitored by the WP leaders and reported to the co-ordinator on a quarterly basis. Here, we summarise the results of this monitoring activity during the third reporting period.

2.1 Workpackage 1

This workpackage is lead by Prof. Gerald Matz, Vienna University of Technology (VUT).

Task 1.1

Contributions within this task have been provided by FhG-HHI, NOK and UNICAL.

Objectives: This task is concerned with adaptive modulation and scheduling and retransmission strategies for MU-MIMO systems taking into account spatiotemporal channel characteristics.

Progress: *Unified framework for general interference functions (FhG-HHI).* Within the reporting period, a main effort within this task was the consolidation and unification of the interference function framework for the analysis of interference-coupled multi-user networks. The fundamental behavior of such a system is described by interference functions, which are generally defined by axioms of nonnegativity, scale-invariance, and monotonicity. It was shown that every interference function has an interpretation as the optimum

of a min-max problem, where the optimization is over a closed comprehensive positive coefficient set. This provides new insight into the structure of general interference functions and its elementary building blocks. Furthermore, it was shown that every closed comprehensive positive set can be expressed as a level set of an interference function. This established a close connection between the analysis of interference functions and multiuser performance regions, which are typically closed comprehensive. The generality of this framework allows for a wide range of potential applications, e.g. the problem of interference balancing.

Convex/concave/log-convex interference functions (FhG-HHI). A major use of interference functions is for the solution of resource allocation problems, specifically for the practically important special case of interference functions with additional properties like convexity, concavity, and log-convexity. Such interference functions occur naturally in various contexts, e.g., adaptive receive strategies, robust power control, or resource allocation over convex utility sets. Our work showed that every convex (concave) interference function can be expressed as a maximum (minimum) over a weighted sum of its arguments. This analytical insight provided a link between the axiomatic interference framework and conventional interference models that are based on the definition of a coupling matrix. Our results can be used to derive best convex/concave approximations for general interference functions. The results have further application for the convex approximation of general feasible sets of multiuser systems. A specific application example we considered was the problem of SINR-constrained power minimization. Here, convexity can be exploited to obtain an iterative algorithm with super-linear convergence.

Another key observation is that any log-convex interference function can be expressed as an optimum over elementary log-convex interference functions. These results contribute to a better understanding of certain quality-of-service (QoS) tradeoff regions, which can be expressed as sublevel sets of log-convex interference functions. The structure of the QoS region was analyzed and conditions for the achievability of boundary points were provided. The proposed framework of log-convex interference functions generalizes the classical linear interference model, which is closely connected with the theory of irreducible nonnegative matrices (PerronFrobenius theory). Applications in robust communication, cooperative game theory, and max-min fairness were considered in specific detail.

Delay-differentiated scheduling (NOK). Another problem addressed within this task was scheduling of users with different delay-requirements in a time-varying wireless channel. The scheduling problem was formulated as a dynamic programming problem, taking into account both user-specific delay

penalties and the time-varying channel state. A scheduling rule similar to the exponential rule was derived, applying dynamic delay-penalized optimization. Threshold-based scheduling optimizes the throughput-delay trade-off in a single-user memoryless channel. Modifications of the optimal single-user scheduling rule to a multiuser channel are studied both in a time-correlated and in a memoryless environment. Numerical experiments suggest that a simplified threshold derived for a memoryless setting performs well in a time-correlated channel. The applicability of the scheduling model to a virtual fading channel with relay nodes was also discussed.

User pairing in MU-MIMO (NOK, UCAL). For the downlink of a multiuser-MIMO transmission system in which at most two users can transmit simultaneously on different spatial channels or beams, we studied how to find the optimal user subsets for K users. In the system considered inter-user interference is mitigated via transmit precoding and sum capacity is maximized using a linear programming algorithm that defines the optimal user subsets under a particular fairness criterion. A similar approach was developed for the uplink of multiuser system. Here, we showed how capacity can be increased by a scheduling strategy, which pairs the transmission of users in different time/frequency/code slots according to the channel quality. The optimal scheduling strategy is equivalent to a combinatorial optimization problem. We show how this problem can be solved efficiently by using the ‘‘Hungarian method.’’ We found that, by using the proposed scheduling scheme, the performance of Minimum Mean Square Error detection approaches the one of Maximum Likelihood detection, as the number of users increases.

Deviations: The work has progressed according to the project schedule.

Deliverables: None during the reporting period.

Task 1.2

The main achievements within this task were obtained by FBM-UPF, UNICAL, and VUT.

Objectives: Task 1.2 is concerned with the design of space-time (ST) coding schemes for multiple-access channels (MACs) and with the joint design of joint ST codes and multiple access schemes.

Progress: *Fast-decodable ST codes (FBM-UPF and UNICAL).* During the reporting period, full-rate, fast-decodable space-time block codes (STBCs)

for 2×2 (Silver Code) and 4×2 multiple-input multiple-output (MIMO) transmission have been developed. Conditions for maximum-likelihood decoding with reduced-complexity have been derived and applied to a unified analysis of two families of 2×2 STBCs that were recently proposed. In particular, a reduced-complexity sphere decoding algorithm suitable for QAM signal constellations was described. Based on this framework, a novel reduced-complexity 4×2 STBC has been designed that outperforms all previously known codes with certain constellations. Furthermore, a multidimensional trellis-coded modulation scheme for MIMO systems based on set partitioning of the Silver Code, named Silver Space-Time Trellis Coded Modulation (SST-TCM), was proposed. This lattice set partitioning is designed specifically to increase the minimum determinant. The branches of the outer trellis code are labeled with these partitions. The Viterbi algorithm is applied for trellis decoding, while the branch metrics are computed by using a sphere-decoding algorithm. It was found that the proposed SST-TCM performs very close to the Golden Space-Time Trellis Coded Modulation (GST-TCM) scheme, yet with a much reduced decoding complexity thanks to its fast-decoding property.

Multi-user space-time codes for the MIMO MAC (UNICAL). We considered multiuser space-time block codes (STBCs) for 2×2 multiple-input multiple-output (MIMO) uplink transmissions, where the information sequences of all users are encoded by individual spacefrequency block codes (SFBC). At the receiver, joint maximum likelihood detection is applied using the sphere decoding algorithm. Using a truncated union bound (UB) approximation, we proposed design criteria of multiuser STBCs for quasi-static fading MIMO multiple access channels (MACs). By combining the structure of algebraic perfect STBCs, we showed how a family of multiuser STBCs can be constructed to fulfill the design criteria and that the proposed STBC outperforms all previously known codes over quasi-static fading MIMO MACs. We further extended our results to frequency-selective channels in the context of MIMO-OFDM transmission. The performance of our designs was corroborated by numerical simulations with explicit STBC designs for two users.

Coded multiple access (VUT). The work on coded multiple access in MIMO systems without any spreading or orthogonal access was continued within the third reporting period. Specifically, interleave division multiple access (IDMA) using simple convolutional codes, random user-specific bit interleavers, and an iterative turbo-like receiver involving a computationally efficient multi-user MIMO detector has been shown to be a practically interesting and viable scheme to realize high-rate multi-user spatial multiplexing

systems. Specifically, we considered a MIMO-IDMA system with increased spectral efficiency due to the use of higher-order symbol constellations. Based on a factor graph framework and the sum-product algorithm, we developed an iterative turbo multiuser receiver. Gaussian approximations for certain messages passed by the sum-product algorithm led to a complexity that scales only linearly with the number of users. To further reduce complexity, we introduced a “selective message update scheme” in which only unreliable messages are updated during the sum-product iterations. Numerical simulations verified the BER performance of the proposed receiver algorithms as well as the desired computational savings. Recent results furthermore suggest that MIMO-IDMA has the potential to approach the sum-capacity in the low-to-medium rate regime.

Deviations: The work has progressed according to the project schedule.

Deliverables: None during the reporting period.

Task 1.3

Within this task, contributions came from partners ETHZ, FhG-HHI, FTW, FBM-UPF, Polito, UNICAL, and VUT.

Objectives: Task 1.3 is concerned with the development of efficient transceiver algorithms (e.g., channel estimation, synchronization, transmit precoding, data detection) for multiantenna channels, with an eye on VLSI implementation complexity.

Progress: *Multi-user detection for unknown number of users.* Conventional multi-user detectors assume that the number of users is exactly known, which in practice often is not the case. At the same time, designing a detector for the wrong number of users can degrade performance significantly. Motivated by this dilemma, a framework for multi-user detection algorithms in situations where the number of users is a-priori unknown was developed based on random set theory. Both the situation where only the (discrete-valued) user data are to be detected as well as the more complicated setup where continuous-valued user parameters (e.g., power levels) have to be estimated simultaneously. Within the third reporting period, specific focus was placed on low-complexity implementations of the detection and estimation algorithms that were derived using random set theory.

Robust and optimum MIMO transceiver design (FhG-HHI, FTW, and Polito). In a number of studies, the problem of how to design MIMO transceivers in situation with imperfect or uncertain channel state information was considered.

Optimum pilot-symbol aided receiver structures for fading MIMO channels have been studied in order to avoid receiver mismatch that results when decoding with a previously estimated MIMO channel matrix. Optimum decoding metrics for various situations have been considered (correlated Rayleigh and Rician fading, noncoherent setup) and iterative implementation suitable for trellis space-time decoding have been proposed in order to reduce the algorithm complexity. During the reporting period, most of the work in this area dealt with corroborating the usefulness of the proposed schemes by applying them to measured real-valued channels.

A similar line of work was concerned with robust worst case designs of MIMO transceivers for systems with imperfect channel state information modeled via an uncertainty set. First we studied the problem of joint transmit and receive filters optimization in a frequency selective, MIMO setup. A framework for the robust optimization of the system was developed by either minimizing the worst-case mean-square-error (MSE) subject to a power constraint or minimizing transmit power subject to a MSE targets for all channels within the uncertainty set. The design algorithms operate in an iterative manner, where each iteration consists of two efficiently solvable semi-definite programs. Proofs of the convergence were provided as well. This approach was subsequently extended to MIMO multiuser downlink wireless systems and, exploiting the convexity of the problem, efficient numerical solutions based on semi-definite programming were derived. Finally, a modification of this work assuming Gaussian CSI mismatch and requiring QoS targets to be satisfied only with certain probability lead to less conservative design compared to strategies based on worst-case optimization.

Sum-rate optimization and capacity balancing for MU-MIMO systems (FhG-HHI). The work here has focused on transceiver design for sum-rate optimization in multiuser MIMO systems with linear processing. Several design criteria have been considered: i) maximization of the weighted sum-rate under a total power constraint; ii) minimization of the total transmit power with a sum-rate requirement; iii) maximization of the minimum rate per user under a total power constraint; iv) minimization of the total transmit power while maintaining certain individual rate requirements. Iterative algorithms have been proposed, which perform optimization in an alternating manner in both virtual uplink and downlink channels. Each iteration contains the optimization of the uplink power, uplink receive filter and downlink receive filter. The power optimization to maximize the sum-rate leads to a Geometric Pro-

gramming (GP) problem. The proposed algorithms outperform the existing schemes and can be extended to receivers performing successive interference cancellation (SIC) in the uplink and interference pre-compensation (IPC) in the downlink.

Data detection (ETHZ and VUT). A major thread of the research dealing with MIMO detection was targeted towards soft instead of hard data detection. On the one hand, sphere decoding (SD) approaches for soft detection were investigated where significant complexity reduction was achieved by using smart tree traversal schemes as well as by clipping of the soft values (log-likelihood ratios) in order to enable more efficient tree pruning. It was seen that close to optimal performance can be achieved at a fraction of the complexity of state-of-the-art SD implementations. In addition, hardware considerations suggested to replace the usual Euclidean norm by the l_∞ norm. Theoretical analyses revealed in spite of lower hardware complexity, l_∞ sphere decoding achieves the same diversity order as conventional sphere decoding. Preceding the sphere decoder with a (partial) linear equalizer was furthermore shown to provide an additional diversity-complexity trade-off. While the diversity results just mentioned have been derived under the assumption of i.i.d. Rayleigh fading, we also found analytical proofs for the fact that for virtually any reasonable MIMO detector, the diversity order remains unchanged for a large class fading distributions (including the case of spatial correlation and Ricean fading).

To obtain a fair comparison of the numerous (soft) MIMO detection schemes developed in the literature, we proposed to use the mutual information of an equivalent modulation channel (between transmit bits and detector soft outputs) as performance measure. The advantage of this approach is its independence from any outer coding scheme. Our numerical results revealed that in the low-rate regime linear MMSE detection is often close to optimal, whereas for high-rate transmissions sphere decoding becomes mandatory. Also, the performance of quadratic MIMO systems using sphere decoding was observed to be approachable using efficient linear detectors by reducing the number of transmit antennas and increasing the size of the symbol constellation.

Lattice reduction algorithms (ETHZ, VUT, UNICAL). Lattice reduction is a powerful technique for improving the MIMO data detection and precoding methods with respect to performance or complexity. For lattice reduction assisted data detection, the LLL algorithm has been considered almost exclusively so far. Within MASCOT, an analytical assessment of the worst-case and average complexity of LLL lattice reduction when applied to fading MIMO channels was obtained. Furthermore, the Seysen algorithm was stud-

ied as an alternative to LLL for MIMO detection. In certain scenarios, the Seysen algorithm outperforms the LLL algorithm in that it finds better lattice bases.

Channel estimation (FBM-UPF and VUT). Reliable channel state information is at the heart of many transceiver algorithms. A novel approach to pilot-symbol assisted channel estimation based on irregular sampling techniques has been developed. This approach is specifically suited to multi-user systems employing OFDMA and yields accurate channel estimates with a very small number of pilots even in situations with strong time and frequency dispersion. Apart of its excellent performance the method is attractive for practical implementations due to its low computational complexity, which does not scale with the number of pilots.

Other work dealing with the channel estimation problem applied random set theory to a scenario where the number of multipath components is not known a priori. Relevant metrics for the estimation problem and the efficient implementation of estimation algorithms based on these metrics have been found.

MIMO precoding (ETHZ and VUT). Vector perturbation has been identified as a promising alternative to dirty paper coding for the downlink of MIMO multi-user systems. During the reporting period, we provided a theoretical analysis of the diversity order that is achievable with vector perturbation precoding in the case of imperfect CSI. The conclusions were that non-reciprocal system with CSI feedback suffer from an error floor (zero diversity) that can be avoided in reciprocal systems with CSI estimation at the base station. Parallel to that, we developed a practically realizable alternative to vector perturbation precoding referred to as transmit outage precoding (TOP). TOP avoids the necessity of communicating power normalization factors to the terminals (feedforward) by using a fixed power normalization and refraining from transmission for poorly conditioned channel realizations. An extension using multiple thresholds and a feasible feedforward scheme was developed in follow-up work. Finally, feedback from WP2 lead to the consideration of vector perturbation precoding and TOP for receivers with limited dynamic range. Here, it was found that appropriately restricting the perturbation vectors at the transmit side is preferable to signal clipping at the receive side.

Deviations: The work has progressed according to the project schedule.

Deliverables: Deliverable D1.3.2, entitled “Baseband transceiver algorithms – final version including feedback from WP2 and WP3 ” and scheduled for M36 was delivered by Dec. 31, 2008.

2.2 Workpackage 2

This workpackage is lead by Prof. Helmut Bölcskei, Eidgenössische Technische Hochschule Zürich (ETHZ).

Task 2.1

Objectives: Research efforts in Task 2.1 focus on assessing the complexity of algorithms and on obtaining a better understanding of the complexity-performance tradeoffs in MU-MIMO systems.

Progress: During the final year of the MASCOT project, only limited effort has been spent for this task, which used to focus on fixed-point requirements and implementation trade-offs of various VLSI designs for MIMO communication. The main contributions consist of publications concluding the work previously spent for this task, for instance on matrix decomposition algorithms such as MMSE sorted QR decomposition (SQRD) or singular value decomposition (SVD). Several papers have been published in order to present and conclude the results, including one paper that was awarded the best student paper award at the 2008 IEEE ISCAS Conference.

Deviations: The work has progressed according to the project schedule.

Deliverables: No deliverables for this task were due in 2008.

Milestones: No milestones for this task were due in 2008.

Task 2.2

Objectives: Task 2.2 is concerned with the development of low-complexity VLSI architectures for algorithms that are most relevant for the successful implementation of MU-MIMO systems and compilation of a library of VHDL reference designs.

Progress: In 2008, this task focused on the composition of the MASCOT VHDL reference design library. The reference library contains four different VHDL reference designs such as sorted QR decomposition, singular value decomposition, lattice-reduction aided precoding using Bruns algorithm, and a K-Best detector.

Deviations: The work has progressed very well.

Deliverables: By December 31, 2008, the deliverable D2.2.1 named “VHDL Library of Reference Designs” has been delivered according to project schedule. This deliverable reports on the VHDL reference design library realized within the MASCOT project and the corresponding licensing procedure in order to obtain the library. The library contains four different VHDL reference designs.

Milestones: Milestone M2.2.2 (Library of VHDL reference designs), due on June 30, 2008, has been reached according to project schedule.

Task 2.3

Objectives: Efforts in Task 2.3 are targeted towards the extension of the ETHZ MIMO testbed to a MU-MIMO system to enable demonstration and performance assessment of MU-MIMO technology. The focus of this year was put on three objectives: First, the characterization and testing of the MIMO Medium Access Control (MAC) algorithms implemented in the MASCOT real-time testbed. The corresponding results are reported in deliverable D2.3.2b. Second, the enhancement of the existing MIMO-OFDM testbed with provisions for advanced MIMO detection and assessment of practical aspects of multi-user MIMO communication. Third, further development of the off-line testbed that allows for experiments and assessments of MU-MIMO algorithms over a real-world wireless channel with off-line signal processing. The results will be demonstrated at the Second ETHZ Open-House Event (Deliverable D4.7) on February 13, 2009, and will be reported in Deliverable D2.3.2c.

Progress: A first major demonstration was presented at the first ETHZ Open-House Event on February 22, 2008 at ETH Zurich. A real-time MU-MIMO setup with three clients was demonstrated, showing data downloads and video streaming from the Internet.

One major activity was the testing and reporting of the MIMO Medium Access Control (MAC) algorithms including the physical and MAC layer characteristics of the MASCOT real-time testbed. Measurement results were provided for both, PHY and MAC layer.

A second major effort was spent on the extension of the MASCOT real-time testbed with sorted QR decomposition (SQRD) for MIMO preprocessing in order to enable advanced MIMO detection schemes. A dedicated ASIC realization of a Givens-Rotations-based SQRD algorithm has been deployed with a custom printed circuit board (PCB) to the MASCOT real-time testbed and is fully operational. The system-level integration of advanced MIMO detection algorithms in the MASCOT real-time testbed is still ongoing.

The last major activity was the enhancement of the offline testbed which allows real-time wireless transmission and offline signal processing in Matlab. With the offline testbed, it is now possible to run single- and multi-user MIMO experiments with different configuration settings (e.g., number of users, individual modulation scheme for each user, frame length, detection algorithm). The offline testbed is an excellent tool for early assessment of advanced MIMO and multi-user communication aspects.

Deviations: The work has progressed according to the revised project schedule.

Deliverables: By June 30, 2008, the deliverable D2.3.2b named “Report on testing of MIMO MAC algorithms” has been delivered. It reports on the testing of the MIMO Medium Access Control (MAC) algorithms including the physical and MAC layer characteristics of the MASCOT real-time testbed.

By February 28, 2009, the Deliverable D2.3.2c named “Report on results for second ETHZ Open-House Event” is due. It will summarize the realized testbed extensions, including the implementation of advanced MIMO and MU-MIMO detection and presents measurement results carried out with the testbed.

As dissemination activity, a video presenting the real-time testbed was produced together with the ETHZ multimedia services.

Milestones: Milestone M2.3.2 (MIMO-MAC algorithms tested), due on June 30, 2008, has been reached according to project schedule.

2.3 Workpackage 3

The research on *Performance Limits* is lead by Prof. Giorgio Taricco, Politecnico di Torino (PoliTo).

Task 3.1 (Partners: PoliTo and FTW)

Objectives: Task 3.1 is concerned with achievable information rates and performance tradeoffs. The performance limit of single-user and multiuser fading channel is to be characterized using asymptotic analysis methods.

Progress: PoliTo and FTW studied the ergodic capacity of the separately correlated Rician fading **wideband** OFDM-MIMO channel. This activity progressed according to the following two investigation lines:

- In the first line, an asymptotic algorithm for the derivation of the ergodic mutual information of the OFDM-MIMO channel has been obtained and then the algorithm was applied to derive the ergodic capacity and the corresponding optimum input signal covariance matrix. The ergodic mutual information maximization algorithm obtained is based on water-filling, similarly to the case of perfect channel state information at the transmitter. The numerical accuracy of the method was investigated and the effectiveness of covariance optimization was assessed with respect to the level of spatial correlation and the Rice factor. The results of this activity are collected in [79].
- In the second line, the ergodic capacity region was investigated by using the asymptotic approach developed in the first line of investigation. A remarkable progress of this activity is due to the fact that the true capacity region was considered here instead of its inner bound consisting of the maximum sum-rate region. The channel model considered is sufficiently general to encompass different spatial correlation matrices for each user and delay at the transmitter and the receiver. Two algorithms have been proposed, which can be used to maximize the (weighted) sum-rates in order to obtain the ergodic capacity region. Both algorithms are based on an asymptotic approximation of the single-user wideband mutual information developed in the first line of investigation. Numerical simulations have shown that the asymptotic approach provides very accurate results even when the number of antennas per user is as small as a few units. The results of this activity are collected in [68].

Deviations: The work has progressed according to the project schedule.

Deliverables: In the original project plan [60, 61], there were no deliverables foreseen during the third reporting period. However, for Amendment 2 [62], it was decided to report the results of this activity in a newly defined Deliverable D3.1.3 due by February 28, 2009. A draft version of Deliverable D3.1.3 is available for review on January 15, 2009.

Task 3.2 (Partners: NOK, ETHZ, VUT, PoliTo, FBM-UPF, UNICAL and FTW)

Objectives: Task 3.2 is concerned with performance tradeoffs in Ad-hoc MIMO networks, outage properties of such networks, and the use of relays.

Progress : FBM-UPF contributed to detection and estimation problems related to neighbor discovery in ad-hoc networks. In addition FBM-UPF studied spectrum sharing (subchannel assignment) methods from the viewpoint of estimation and detection theory. These results are reported in Deliverable 3.2.1 and in related references therein.

Nokia studied subchannel assignment in OFDMA systems as a resource allocation problem, and posed the problem using linear programming and majorization theory. These techniques were considered in particular for OFDMA relay networks. This work started in 2007 and the results are reported in Deliverable 3.2.1 and in related references therein. During 2008, Nokia and UNICAL developed methods for relay assignment in a multiuser network, where a different source nodes must be using a distinct subset of relays.

ETHZ contributed to the study of a MIMO relay network with multiple source-destination pairs. ETHZ developed a distributed algorithm for controlling the relay nodes. It was proved that the distributed algorithm effectively decouples the source-destination pairs and the network achieves full spatial multiplexing gain and crystallization. Furthermore, ETHZ considered code design and diversity multiplexing tradeoff in multiple access MIMO channels. These results are reported in Deliverable D3.2.1 and in related references therein. During 2008, ETHZ analyzed fading relay networks, where L users with M -antenna each communicate with an N -antenna destination terminal through a set of half-duplex relays using a half-duplex relaying protocol with linear processing at the relay level. ETHZ derived the diversity multiplexing tradeoff curve under the assumption that relays employ unitary transformations.

During 2008, VUT and Nokia contributed to signalling mechanisms for distributed beamforming with multiple half-duplex amplify-and-forward relays. The first proposed method applied deterministic perturbations and scalable (1-bit) feedback (from the destination to the relays). It does not require, in contrast to previous work, CSI knowledge at the relays. Subsequently, the general approach was further developed with multiplicative perturbations as opposed to additive perturbations. Multiplicative perturbations, based on Givens rotations, adapt the beamforming weights while guaranteeing a sum power constraint for the relays. This perturbation scheme is shown to be computationally efficient and easy to design, thus allowing for low-complexity relay nodes. This work is reported in Deliverable D3.2.2. This work uses a signal processing approach and complements the theoretical work (code design, outage properties, DMT, etc) reported in for ETHZ.

The work of FTW and PoliTo focused on theoretical analysis of large random wireless ad hoc networks, where the underlying node distribution is previously almost ubiquitously assumed to be the homogeneous Poisson point process. Previous work is extended to account for random node distribution and its effect on scaling laws. This could be seen as a first attempt to connect some overoptimistic results based on stochastic channel model to more realistic analysis, relying on electromagnetic propagation arguments. These results, and other related scaling law results are documented in Deliverable 3.2.2 and references therein.

Deviations: The work has progressed according to the project schedule.

Deliverables: Two deliverables were due during the reporting period, namely Deliverable 3.2.1, due March 31, 2008, and Deliverable 3.2.2 due by February 28, 2009. A draft of Deliverable D3.2.2 is available by January 15, 2008.

2.4 Workpackage 4

The dissemination activities are lead by Prof. Christoph Mecklenbräuker, Forschungszentrum Telekommunikation Wien (FTW).

2.4.1 Web-site

The public web-site [29] is continuously updated. Here, the project announces events, tutorials, special sessions, publications, deliverables, and achievements.

<http://www.ist-mascot.org>

2.4.2 Publications

Details on the publication plans and policy can be found in MASCOT Deliverable D4.2. MASCOT's list of publications can be found at the end of this final report.

Journals

MASCOT contributions have been submitted to a number of important international journals during 2008:

- IEEE Journal on Selected Areas in Communications (JSAC),
- IEEE Journal on Selected Topics in Signal Processing (JSTSP),
- IEEE Transactions on Information Theory (TIT),
- IEEE Communications Letters (CL),
- European Transactions on Telecommunications (ETT).

Journal Special Issues

For the IEEE Journal on Selected Topics in Signal Processing (JSTSP), a special issue on *Managing Complexity in Multiuser MIMO Systems* is currently being edited by associate editors Gerald Matz (VUT), Emanuele Viterbo (UNICAL), Robert Calderbank (Princeton University), Ayman Naguib (Qualcomm Inc.), and Christoph Mecklenbräuer (FTW). Around 30 manuscripts were submitted in total for publication in September 2008 and are currently being reviewed. Further information is available online¹.

During 2008, Ari Hottinen (Nokia) was a co-guest-editor (together with M. Shafi, H. Huang, P. J. Smith, and R. A. Valenzuela) for IEEE Journal on Selected Areas on Communications (Volume: 26 Issue: 6 Date: August 2008) special issue on "MIMO Systems and Applications: Field Experience, Practical Aspects, Limitations, and Challenges".

¹see http://www.et.byu.edu/groups/ece_jstsp/

2.4.3 WSA 2009

FhG-HHI organises the ITG/IEEE Workshop on Smart Antennas (WSA 2009) in Berlin, Germany on February 16–19, 2009. The WSA 2009 homepage is online available at the following URL

<http://www.mk.tu-berlin.de/wsa2009>

and accessible via the MASCOT homepage:

<http://www.ist-mascot.org/wsa-2009> .

2.4.4 Second Industry Course on MU-MIMO

MASCOT Deliverable D4.6 is the *Second industry course on MU-MIMO*. The goal of this second industry course is to provide an introduction and overview of state-of-the-art research in multiuser MIMO. For selected topics we will provide background material as well as new results that have been obtained within the MASCOT project. The course is held as a WSA 2009 tutorial on February 16, 2009.

The programme of the Second industry course is available at the following link: <http://www.ist-mascot.org/industry-course-II>.

The following topics are discussed:

1. Capacity limits for MU-MIMO fading channels
2. MU-MIMO detection and demodulation
3. Interference and resource allocation in MU-MIMO wireless systems
4. Neighbor discovery in MU-MIMO wireless networks
5. Multipath channel estimation for MU-MIMO wireless networks

List of Contributors

Biglieri, E.	FBM-UPF
Jaldén, J.	VUT
Riegler, E.	FTW
Schubert, M.	FhG-HHI

2.4.5 Second ETHZ Open House Event

The Second ETHZ Open House Event (Deliverable D4.7) is planned for Friday, February 13, 2009.

The goal of the second ETH Zurich open-house event is to present selected results. Focus is on the design, assessment, implementation, and demonstration of multi-user MIMO wireless systems. In the first part of the open-house event, the MASCOT partners give a series of talks covering various theoretical, algorithmic, and implementation aspects of multi-user MIMO systems. In the second part, the multi-user MIMO-OFDM testbed, which has been developed at ETH Zurich (partly within MASCOT), will be demonstrated. Here, the emphasis will be on recently implemented advanced MIMO detection algorithms and on collision-based multi-user MIMO uplink transmission.

Further details on the programme and registration can be found at the following link:

<http://www.ist-mascot.org/deliverables/deliverable-4.7/>

2.4.6 Special session during 2008

The following special session was organised to publish results from the MASCOT project and held in 2008:

EUSIPCO 2008. A special session on “Complexity Reduction in Multiuser MIMO Systems”, chairs: Gerald Matz (VUT) and Christoph Mecklenbräuker (FTW), Lausanne, Switzerland, in August 2008. Current practical MIMO implementations are still far from theoretical performance limits because system designers are experiencing difficulties to reconcile the complexity of sophisticated MIMO techniques with the implementation constraints imposed by existing hardware. Thus, one of the main challenges in the realization of multiuser MIMO wireless systems - and in fact a critical factor for the success of MIMO in WiMAX, WiFi, and beyond 3G - is the efficient implementation of advanced MIMO concepts. Here, the goal is to devise tunable algorithms that use clever complexity reduction techniques (especially at the receiver side) to achieve graceful performance degradation. This special session intends to promote this important new thread in MIMO research by bringing together some of the top experts in the field. The MASCOT project’s contributions [6, 15, 32] focus on reduced-complexity MIMO detection schemes (advanced sphere decoding and lattice reduction algorithms). Two additional papers complemented this session: The first proposes and analyses cognitive decoding for space-time codes² whereas the second evaluates the MU-MIMO performance of specific

²S. Sirianunpiboon, A.R. Calderbank, and S.D. Howard: “Cognitive Decoding and the Golden Code”, in Proc. EUSIPCO 2008.

low-complexity receivers by measurements³.

2.4.7 WinTech'08 Demo Contest

The Third International Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization (WinTech'08) was carried out in conjunction with the ACM MobiCom'08 Conference on September 19, 2008 in San Francisco (CA), USA. The MASCOT Real-Time 4×4 Multiuser MIMO-OFDM Textbed won the very honourable **Second Place** at the WinTech'08 Demo Contest. The winners are:

First Place: *Machine Learning for Physical Layer Link Adaptation in Multiple-Antenna Wireless Networks* by Robert C. Daniels, Ketan Mandke, Steven W. Peters, Scott M. Nettles, and Robert W. Heath, Jr. (The University of Texas at Austin, USA)

Second Place: *Multi-User MIMO Testbed* [50] by Peter Luethi, Markus Wenk, Wolfgang Fichtner, and Helmut Bölcskei (ETH Zurich, Switzerland)

Third Place: *A Demonstration of Video over a Cooperative PHY layer Protocol* by Shashi Raj Singh, Ehtesham Akhtar Siddiqui, Thanasis Korakis, Pei Liu, and Shivendra S. Panwar (Polytechnic Institute of NYU and IIT Kanpur)

For further details please see the following links:

http://www.ruf.rice.edu/~mobile/WINTECH2008/demo_contest.htm

<http://www.sigmobile.org/mobicom/2008/index.html>

2.4.8 Podcasts

During the First ETHZ Open House Event, a video about the MASCOT Real-Time Multi-User MIMO Testbed was recorded and subsequently edited and dubbed. It is available via online streaming from the following link:

<http://www.podcast.ethz.ch/episodes/?id=734>

2.4.9 Contributions to standardisation

In the context of a bilateral cooperation between FhG-HHI and Siemens (today: Nokia Siemens Networks), some MASCOT research results on inter-

³C. Mehlführer, S. Caban, and M. Rupp: "Measurement Based Evaluation of Low Complexity Receivers for D-TxAA HSDPA", in Proc. EUSIPCO 2008.

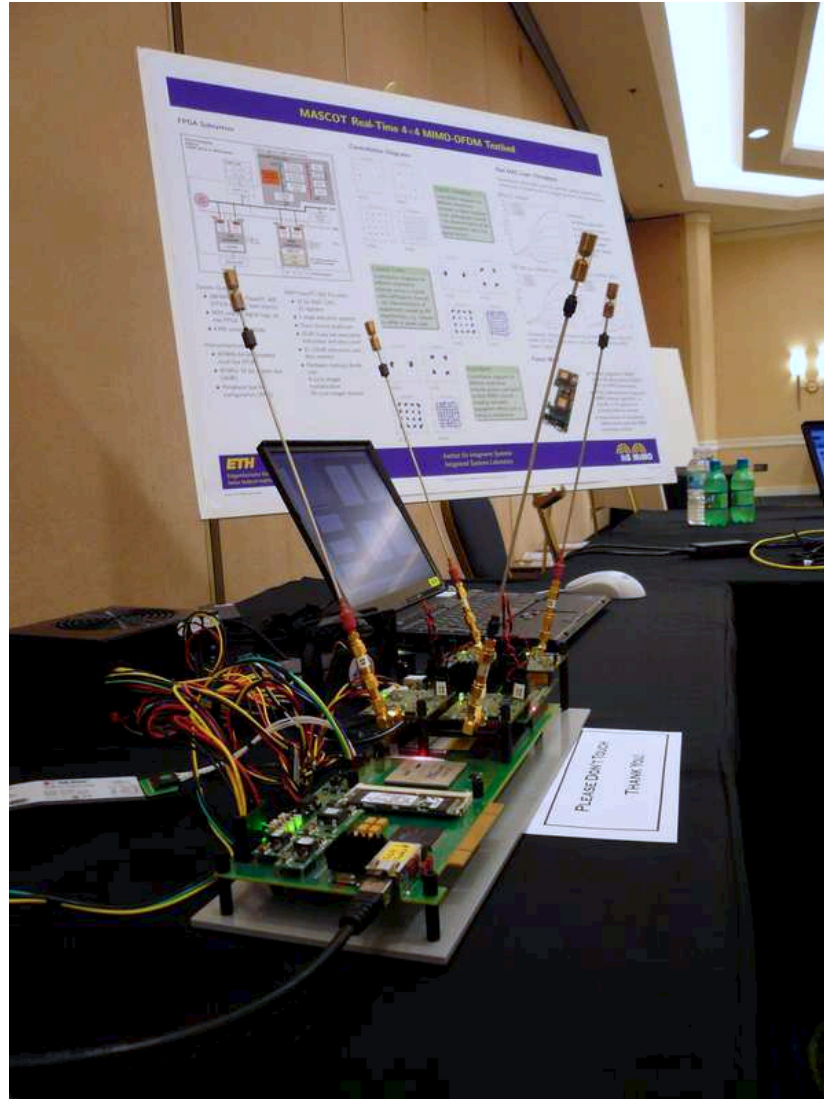


Figure 2.1: Multi-User MIMO Testbed at WinTech'08 Demo Contest, San Francisco, Sep. 19, 2008

ference management and precoding were contributed to the standardisation of 3GPP Long Term Evolution during 2006^{4,5,6}.

The use of the Golden space-time code in an IEEE 802.16e (WiMax) system with future MIMO-OFDM enhancements was benchmarked in a simulation study. This research was carried out jointly by the partners NOKIA, UNICAL, VUT, and FTW and the results were published at the ITG/IEEE Workshop on Smart Antennas (WSA 2007)⁷.

Nokia contributed "Multidimensional rotated constellations for fast fading channels" by Emanuele Viterbo, for discussion in DVB-T2 forum in September 2007. Emanuele Viterbo wrote a contribution on the Golden code for DVB-H. This contribution was discussed informally with delegates.

2.4.10 Exploitation activities

Intellectual Property Right management

The project partners established an IPR Policy Committee consisting of technical experts and legal experts in September, 2006⁸. This committee defines rules and guidelines for the reuse of existing knowledge (PEKH, Pre-Existing Know-How, Background) and the tracking of new knowledge generation (Knowledge, Foreground) in the project.

The IPRs generated by the project are evaluated by the IPR Policy Committee for patent filing⁹ or for exploitation. The actual patent filing itself is performed by the partners involved. The goal is to build up and maintain a MASCOT IPR portfolio¹⁰.

⁴3GPP TSG RAN WG1 LTE ad hoc, R1-061899, Interference minimization and cancellation techniques for MIMO systems, Cannes, France, Jun. 27–30, 2006.

⁵3GPP TSG RAN WG1 LTE ad hoc, R1-062301, Optimum combination of interference coordination and cancellation, Tallinn, Estonia, Aug. 28–Sep. 1, 2006.

⁶3GPP TSG RAN WG1 LTE ad hoc, R1-063245, Performance considerations for unitary versus non-unitary precoding, Riga, Latvia, Nov. 6–10, 2006.

⁷A. Hottinen, Y. Hong, E. Viterbo, C. F. Mecklenbräuker, and C. Mehlführer. *A comparison of high rate algebraic and non-orthogonal STBCs*. In *Proc. ITG/IEEE Workshop on Smart Antennas (WSA 2007)*, Vienna, Austria, February 2007.

⁸see Technical Annex (Description of Work): [60], Section 6.2.2, page 19.

⁹Note: Some MASCOT partners may refuse to send invention reports to external bodies as a matter of policy.

¹⁰The MASCOT IPR portfolio is understood as a list of IPRs filed within MASCOT to be handled according to the MASCOT Consortium Agreement

Licensing plan

A VHDL library of 4 selected MU-MIMO transceiver algorithms is developed within WP2 with input from WP1. Under the lead of ETH Zurich, and subject to a mutually acceptable agreement with the other involved MASCOT partners, components from this library may be commercially licensed to the European industry¹¹. The legal support of ETH Transfer, the technology transfer department of ETH Zurich, will then be solicited in questions relating to invention protection and exploitation, as well as preparation and negotiation of relevant contracts with potential industrial partners. Similar services will be provided by corresponding units at FhG-HHI, PoliTo, and VUT (see Table 2.1) on a per partner basis.

PoliTo has an office dealing with IPR management, also dealing with patents. There is a new regional technology transfer office, in which PoliTo participates, that acts as an industrial liaison office (ILO) for the three universities of Piedmont. The target of this ILO is to provide a coordinated system for the management of IPR.

At VUT, the Technology Transfer Unit of the Department of External Relations (Außeninstitut) assists with the protection of IPR, filing of patents, and exploitation activities.

¹¹see Technical Annex [60], WP4 Summary, page 66.

1	FTW	internal responsible: Dr. C.F. Mecklenbräuker
2	NOKIA	internal
3	FhG-HHI	Dept. B9 – Patents and Licensing Dr. Michael Groß
4	PoliTo	regional technology transfer office for the three universities of Piemont.
5	VUT	Außeninstitut, Technologie Transfer http://www.tuwien.ac.at/dienstleister/technologietransfer
6	ETHZ	ETH Transfer http://www.vpf.ethz.ch/transfer/index.EN
7	FBM-UPF	Business innovation & development responsible: Ms. Marta Ysern
8	UNICAL	Commissione per la valorizzazione dei risultati della ricerca e trasferimento tecnologico responsible: Prof. Riccardo Barberi

Table 2.1: Technology transfer institutions which will aid in exploitation, especially concerning the licensing of the VHDL reference designs.

Chapter 3

Consortium Management

3.1 Project Steering Committee

The members of the project steering committee (PSC) are [60, 61, 62]:

1. C.F. Mecklenbräuker (FTW)
2. A. Hottinen (NOK)
3. M. Schubert (FhG-HHI)
4. G. Taricco (PoliTo)
5. G. Matz (VUT)
6. H. Bölskei (ETHZ),
7. E. Biglieri (FBM-UPF),
8. E. Viterbo (UNICAL).

During the third reporting period, the PSC convened four times:

- 9th PSC meeting, Zürich, February 22, 2008.
- 10th PSC meeting, Phone Conference, May 26, 2008.
- 11th PSC meeting, Nokia Research Center, Lausanne, Switzerland, on Sep 29, 2008.
- 12th PSC meeting, Zürich, February 13, 2009.

Detailed PSC meeting minutes document the discussions during these meetings and the agreed decisions. The PSC meeting minutes are available in the reviewer's section of the MASCOT web-site:

<http://www.ist-mascot.org/review/supplementary-reports/>

3.2 Liaison between MASCOT and SURFACE

During June 2006, a liaison between the two FP6–IST projects SURFACE [30] and MASCOT [29] was established. Both projects participate in the Broadband Air Interfaces (BAI) cluster which is moderated by Sylvie Mayrargue (CEA–LETI) [53]. After the first BAI Cluster meeting in February 2006, it became clear that the SURFACE and MASCOT projects would mutually benefit from a closer cooperation than mere participation in the BAI Cluster would enable.

This liaison aims at coordinating the scientific scopes of both projects. It is believed by the participants that both projects will complement each other well because both projects attack challenges in multiuser MIMO communication systems (by theoretical investigations and numerical evaluation). Whereas SURFACE focusses on simulation and software tooling including the design of algorithms for field programmable gate arrays (FPGA) and deployment cost analysis¹, MASCOT implements VHDL reference designs (Deliverable D2.2.1) for application specific integrated circuits (ASIC) and validates them on a hardware testbed (Deliverable D2.3.2c).

The liaison aims at a close cooperation on dissemination and exploitation.

3.3 Short Visits

- Ezio Biglieri (FBM-UPF) visited Ari Hottinen (Nokia) from September 15, 2008 until September 30, 2008.
- Ezio Biglieri (FBM-UPF) visits Helmut Bölcskei (ETHZ) from February to May 2008.
- Peter Fertl (VUT) was on-leave from VUT as a guest researcher at Nokia during Summer 2008.
- Emanuele Viterbo was on-leave from UNICAL as a visiting scientist at Nokia during Summer 2008.
- Joakim Jaldén (VUT) visits Helmut Bölcskei (ETHZ) from August to September 2008 for joint work on complexity analysis of sphere decoding.
- Giulio Coluccia (PoliTo) visited Erwin Riegler (FTW) and Christoph Mecklenbräuer (FTW) from May 22, 2007 until June 08, 2007.

¹see SURFACE Deliverables D7.4, D8.2, and D8.3

- Peter Fertl (VUT) visited Ari Hottinen (Nokia) from July 02, 2007 until September 30, 2007. During his stay at Nokia he visited Helmut Bölcskei (ETHZ) from August 17.8.2007 until August 21, 2007.
- Yi Hong (UNICAL) visits Helmut Bölcskei (ETHZ) during 26—31 July 2007 for setting a collaboration on Algebraic multiuser STBC
- Yi Hong (UNICAL) visits Ezio Biglieri (FBM-UPF) during 21—24 May 2007 for setting up a collaboration on STBC
- Emanuele Viterbo (UNICAL) visits Ezio Biglieri (FBM-UPF) in Barcelona during 21—24 May 2007 for setting up a collaboration on STBC and presenting a tutorial on sphere decoding
- Emanuele Viterbo (UNICAL) visits Ari Hottinen (Nokia) in Helsinki during 25—28 March, 2007 for a presentation on Golden space-time trellis coded modulation and setting up a collaboration on STBC and long term visit plan.
- Emanuele Viterbo (UNICAL) visits Helmut Bölcskei(ETHZ) during 28—30 March, 2007 for a presentation on Golden space-time trellis coded modulation and setting up a collaboration on multiuser STBC.

Chapter 4

Other Issues

There are no other issues to report for MASCOT.

Chapter 5

Annex — Plan for using and disseminating the knowledge

5.1 Exploitable knowledge and its Use

The four baseband transceiver algorithms included in the VHDL Reference Designs (MASCOT Deliverable D2.2.1) are

- Sorted QR Decomposition (SQRD),
- Singular Value Decomposition (SVD) ,
- Lattice-reduction aided precoding using Brun’s algorithm, and a
- K -Best detector.

Exploitable Knowledge	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) Involved
Sorted QR Decomposition	VHDL library	ICT	End of the project	License	MASCOT
Singular Value Decomposition	VHDL library	ICT	End of the project	License	MASCOT
Lattice-Reduction Aided Precoding	VHDL library	ICT	End of the project	License	MASCOT
K -Best Detector	VHDL library	ICT	End of the project	License	MASCOT
Adhoc MIMO Network Algorithms	t.b.d.	ICT	End of the project	4 patent applications	Nokia

Table 5.1: Overview Table - Exploitable knowledge and its Use

Licensing plan

A VHDL library of 4 selected MU-MIMO transceiver algorithms is developed within WP2. Under the lead of ETHZ, and subject to a mutually acceptable agreement with the other involved MASCOT partners, components from this library may be commercially licensed to the European industry¹. The legal support of ETH Transfer, the technology transfer department of ETH Zurich, will then be solicited in questions relating to invention protection and exploitation, as well as preparation and negotiation of relevant contracts with potential industrial partners. Similar services will be provided by corresponding units at FhG-HHI, PoliTo, and VUT (see Table 2.1) on a per partner basis.

PoliTo has an office dealing with IPR management, also dealing with patents. There is a new regional technology transfer office, in which PoliTo participates, that acts as an industrial liaison office (ILO) for the three universities of Piedmont. The target of this ILO is to provide a coordinated system for the management of IPR.

At VUT, the Technology Transfer Unit of the Department of External Relations (Außeninstitut) assists with the protection of IPR, filing of patents, and exploitation activities.

5.2 Dissemination of Knowledge

Planned/Actual Dates	Type	Type of audience	Countries adressed	Size of audience	Partner responsible/involved
Feb. 2008	1st ETHZ Open House Event	Higher Education Research	Europe	30	ETHZ
Aug. 2008	EUSIPCO 2008 Special Session on Complexity Reduction	Higher Education Research	Europe	N/A	FTW
Feb. 2009	2nd ETHZ Open House Event	Higher Education Research	Europe	20	ETHZ
Feb. 2009	2nd MU-MIMO Industry Course	Higher Education Research	Europe	30	FTW / FBM-UPF / FhG HHI

Table 5.2: Overview Table - Dissemination of Knowledge

¹see Technical Annex [60], WP4 Summary, page 66.

5.2.1 Web-site and Content Management System

A public web-site is used for announcing events, tutorials, publications, deliverables, and achievements. It is accessible through the following URL:

<http://www.ist-mascot.org>

MASCOT's external announcements (e.g. events, publications, deliverables) and internal file sharing are organised via a content management system. It is accessible through the following URL:

<http://plone.ist-mascot.org>

5.2.2 Special session in 2008

EUSIPCO 2008. A special session on “Complexity Reduction in Multiuser MIMO Systems”, organisers: Gerald Matz and Christoph Mecklenbräuker, August 2008.

- “Cognitive decoding and the Golden code,” by A. Robert Calderbank (Princeton University - Department of Electrical Engineering), Stephen D. Howard, and Songsri Sirianunpiboon (both at Defence Science and Technology Organisation - Australian Department of Defence)
- “Soft Sphere Decoder for an Iterative Receiver in Time-varying MIMO Channels,” by Charlotte Dumard and Thomas Zemen (both at FTW).
- “Multiuser detection with an unknown number of active users: receiver design,” by Daniele Angelosante (Universita degli Studi di Cassino - Laboratorio di Informatica e Telecomunicazioni), Ezio Biglieri (FBM-UPF), and Marco Lops (Universit degli Studi di Cassino - Laboratorio di Informatica e Telecomunicazioni)
- “Silver Space–Time Trellis Coded Modulation,” by Ezio Biglieri (FBM-UPF), Yi Hong, and Emanuele Viterbo (UNICAL)
- “Measurement Based Evaluation of Low Complexity Receivers for D-TxAA HSDPA,” by Christian Mehlführer, Sebastian Caban, and Markus Rupp (all from Vienna University of Technology).

5.2.3 Second MU-MIMO Industry Course

The Second MU-MIMO Industry Course (MASCOT Deliverable D4.6) is organised as a half-day tutorial during WSA 2009, Berlin, February 2009. The

aim of this tutorial is to provide an introduction and overview of state-of-the-art research topics in multiuser MIMO. We will focus on the following three topics which will be presented by leading researchers in the corresponding areas:

- Random-set theory and its applications to wireless communications (Ezio Biglieri): Random-set theory (RST) is a probability theory of finite sets that exhibit randomness not only in each element, but also in the number of their elements. RST can provide the tool of choice for the solution of a number of problems in wireless communication, like multiuser detection in which the number of active users is unknown and time-varying, or a changing number of paths in frequency selective channels.
- Interference and Resource Allocation in Wireless Systems (Martin Schubert): Interference between users is one of the main hurdles to provide high-rate services for densely populated user environments. In this presentation we will investigate adaptive signal processing and resource allocation/scheduling strategies with an emphasis on multiuser MIMO. We also present an interesting connection to cooperative game theory (Nash bargaining) and address the problem of transceiver optimization with different power constraints.
- Capacity limits of multiuser MIMO systems (Erwin Riegler): Multiuser MIMO systems are becoming increasingly common and it is important to understand the underlying fundamental limits on reliable communication. In this tutorial we will present recent results on the capacity region for certain classes of channel models. We will show how special points in this region can be achieved and also discuss several channel information feedback strategies. We assume basic knowledge on probability and random processes, multiuser detection theory, optimization theory and MIMO.

5.2.4 Publications

Details on the publication plans and policy can be found in MASCOT Deliverable D4.2. MASCOT's list of publications for 2008 and 2009 can be found in the bibliography of this Final Activity Report.

Journals

MASCOT contributions have been submitted to a number of important international journals during 2008:

- IEEE Journal on Selected Areas in Communications,
- IEEE Journal on Selected Topics in Signal Processing,
- IEEE Transactions on Signal Processing,
- IEEE Transactions on Information Theory,

5.3 Publishable results

- The MASCOT deliverables are publicly available on the web-site at the following URL <http://www.ist-mascot.org/deliverables>
- In Section “Publications 2008—2009”, on pages NN–NN, all scientific publications resulting from MASCOT research during the third reporting period are listed.

Publications 2008—2009

- [1] G. Alfano, M. Guillaud, and A. Tulino. Scaling laws for large ad-hoc wireless networks with wishart-poisson fading. In *Proc. International Symposium on Spread Spectrum Techniques and Applications (ISSSTA)*, Bologna, Italy, Aug. 2008.
- [2] G. Alfano, A. Tulino, and M. Guillaud. High and low-SNR regimes for stochastic networks. In *Proc. International Symposium on Information Theory and its Applications (ISITA)*, Auckland, New Zealand, Dec. 2008.
- [3] D. Angelosante, E. Biglieri, and M. Lops. Low-complexity receivers for multiuser detection with an unknown number of active users. In *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Las Vegas (NV), USA, March 30–April 4 2008.
- [4] D. Angelosante, E. Biglieri, and M. Lops. Low-complexity receivers for multiuser detection with an unknown number of active users. *IEEE Trans. Sign. Proc.*, submitted for publication, Nov. 2008.
- [5] D. Angelosante, E. Biglieri, and M. Lops. Multiple target tracking using random sets. In *EUSIPCO 2008*, Lausanne, Switzerland, August 2008.
- [6] D. Angelosante, E. Biglieri, and M. Lops. Multiuser detection with an unknown number of active users: Receiver design. In *EUSIPCO 2008*, Lausanne, Switzerland, August 2008. [24](#)
- [7] D. Angelosante, E. Biglieri, and M. Lops. Sequential estimation of multipath MIMO-OFDM channels. In *Proc. 2nd OFDM Workshop*, Santa Clara University (CA), USA, Oct. 30-31 2008.
- [8] D. Angelosante, E. Biglieri, and M. Lops. Sequential estimation of multipath MIMO-OFDM channels. *IEEE Trans. Sign. Proc.*, submitted for publication 2008.

- [9] D. Angelosante, E. Biglieri, and M. Lops. Sequential estimation of time-varying multipath channel for MIMO-OFDM systems. In *Proc. IEEE Int. Symp. on Inf. Theory (ISIT)*, Toronto (ON), Canada, July 6–11 2008.
- [10] D. Angelosante, E. Biglieri, and M. Lops. Some applications of FISST to wireless communications. In *Proc. 11th International Conference on Information Fusion*, Cologne, Germany, June 30–July 3 2008.
- [11] D. Angelosante, E. Biglieri, and M. Lops. Multiuser detection in a dynamic environment — Part II: Joint user identification and parameter estimation. *IEEE Trans. Inform. Theory*, to be published 2009.
- [12] E. Biglieri. Sphere decoding is coming of age. In *Joint Workshop on Coding and Communications (JWCC 2008)*, St. Helena (CA), USA, October 2008.
- [13] E. Biglieri, E. Grossi, M. Lops, and A. Tauste Campo. Large-system analysis of a CDMA dynamic channel under a Markovian input process. In *Proc. IEEE Int. Symp. on Inf. Theory (ISIT)*, Toronto (ON), Canada, July 6–11 2008.
- [14] E. Biglieri, Y. Hong, and E. Viterbo. On fast-decodable space-time block codes. In *International Zurich Seminar*, ETH Zurich, Switzerland, March 2008.
- [15] E. Biglieri, Y. Hong, and E. Viterbo. Silver space-time trellis-coded modulation. In *EUSIPCO 2008*, Lausanne, Switzerland, August 2008. [24](#)
- [16] E. Biglieri, Y. Hong, and E. Viterbo. On fast-decodable space-time block codes. *IEEE Trans. Inform. Theory*, to be published 2009.
- [17] H. Boche. Stable linear systems and sampling. In *Joint Workshop on Coding and Communications (JWCC 2008)*, St. Helena (CA), USA, October 2008.
- [18] H. Boche and M. Schubert. Concave and convex interference functions – general characterizations and applications. *IEEE Trans. Sign. Proc.*, 56(10, Part I):4951–4965, 2008. Parts of the results were published at ITG/IEEE Workshop on Smart Antennas (WSA) 2007, Vienna, Austria.

- [19] H. Boche and M. Schubert. The structure of general interference functions and applications. *IEEE Trans. Inform. Theory*, 54(11):4980–4990, November 2008.
- [20] H. Bölcskei. Geometric aspects of the diversity–multiplexing tradeoff in ISI fading MIMO channels. In *Joint Workshop on Coding and Communications (JWCC 2008)*, St. Helena (CA), USA, October 2008.
- [21] J. Boutros, E. Viterbo, and G. Cohen. Convolutional tanner structures for non-ergodic wireless channels. In *Proc. IEEE Int. Symp. on Inf. Theory (ISIT)*, Toronto, Canada, July 2008.
- [22] L. Bruderer, C. Studer, M. Wenk, D. Seethaler, and A.P. Burg. VLSI implementation of the LLL lattice-reduction algorithm for MIMO detection. in preparation, 2009.
- [23] A. Tauste Campo and E. Biglieri. Asymptotic capacity of static multiuser channels with an unknown number of users. In *WPMC 2008*, Lapland, Finland, September 2008.
- [24] B. Cerato, G. Masera, and E. Viterbo. Decoding the Golden space-time trellis coded modulation. *IEEE Comm. Lett.*, 12(8):569–571, August 2008.
- [25] B. Cerato, G. Masera, and E. Viterbo. Enabling VLSI processing blocks for MIMO-OFDM communications. *VLSI Design*, 2008:1–10, January 2008. Article ID 351962.
- [26] B. Cerato, G. Masera, and E. Viterbo. Decoding the Golden code: a VLSI design. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 17(1):156–160, January 2009.
- [27] G. Coluccia, E. Riegler, C. Mecklenbrauker, and G. Taricco. Optimum MIMO-OFDM detection with pilot-aided channel state information. *IEEE Journal of Selected Topics in Signal Processing*, submitted 2008.
- [28] G. Coluccia, E. Riegler, C.F. Mecklenbräuker, and G. Taricco. Optimum MIMO-OFDM receivers with imperfect channel state information. In *Proc. IEEE Globecom*, New Orleans (LA), USA, Nov 30 — Dec 4 2008.
- [29] C.F. Mecklenbräuker (Project Coordinator). Multiple Access Space-Time Coding Testbed (MASCOT). <http://www.ist-mascot.org>. 21, 31

- [30] J.R. Fonollosa (Project Coordinator). Self configurable air interface (SURFACE). <http://www.ist-surface.org>. 31
- [31] Pedro Coronel, Markus Gärtner, and Helmut Bölcskei. Diversity-multiplexing tradeoff in selective-fading multiple-access MIMO channels. In *IEEE Int. Symposium on Information Theory (ISIT)*, July 2008.
- [32] C. Dumard, J. Jaldén, and T. Zemen. Soft sphere decoder for an iterative receiver in time-varying MIMO channels. In *EUSIPCO 2008*, August 2008. 24
- [33] P. Fertl, A. Hottinen, and G. Matz. Perturbation-based distributed beamforming for wireless relay networks. In *IEEE Globecom 2008*, New Orleans (LA), USA, November 2008.
- [34] P. Fertl, A. Hottinen, and G. Matz. A multiplicative weight perturbation scheme for distributed beamforming in wireless relay networks with 1-bit feedback. In *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Taipei (Taiwan, R.O.C.), to be published April 2009.
- [35] P. Fertl, J. Jaldén, and G. Matz. Capacity-based performance comparison of MIMO-BICM demodulators. In *Proceedings of the IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2008)*, Recife, Brazil, July 2008.
- [36] T. Heikkinen and A. Hottinen. Delay-differentiated scheduling in a fading channel. *IEEE Transactions on Wireless Communications*, 7(3):848–856, March 2008.
- [37] T. Heikkinen and A. Hottinen. Distributed scheduling via pricing with partial orthogonality. In *6th @WAS International Conference on Mobile Computing and Multimedia (MoMM'2008)*, Linz, Austria, November 2008.
- [38] Y. Hong, S. Shamai, and E. Viterbo. Algebraic-phase scrambling sequences for code-spread code-division multiple-access. In *Proc. IEEE Int. Symp. on Inf. Theory (ISIT)*, Toronto, Canada, 2008.
- [39] Y. Hong and E. Viterbo. Algebraic multiuser space-time block codes for 2x2 MIMO. In *PIMRC 2008*, Cannes, France, September 2008. invited.
- [40] Y. Hong and E. Viterbo. Algebraic multiuser spacefrequency block codes. In *Proc. IEEE Internat. Symp. on Spread Spectrum Techniques*

- and Applications (ISSSTA)*, Bologna, Italy, August 2008. to be published.
- [41] A. Hottinen and E. Viterbo. Optimal user pairing in downlink multiuser MIMO with transmit precoding. In *4th workshop on Resource Allocation in Wireless Networks (RAWNET)*, Berlin, Germany, March 2008.
 - [42] H. Huang, M. Trivellato, A. Hottinen, M. Shafi, P.J. Smith, and R. Valenzuela. Increasing downlink cellular throughput with limited network MIMO coordination. *IEEE Trans. Wireless Communications*, to be published 2009.
 - [43] J. Jaldén and G. Matz. MIMO receiver diversity in general fading. In *IEEE ICASSP 2008*, Las Vegas (NV), USA, 2008.
 - [44] J. Jaldén, J. Maurer, and G. Matz. On the diversity order of vector perturbation precoding with imperfect channel state information. In *Proc. IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2008)*, Recife, Brazil, July 2008.
 - [45] J. Jaldén, D. Seethaler, and G. Matz. Worst- and average-case complexity of LLL lattice reduction in MIMO wireless systems. In *IEEE ICASSP 2008*, Las Vegas (NV), USA, 2008.
 - [46] S. Kittipiyakul, P. Elia, and T. Javidi. High-SNR analysis of outage-limited communications with bursty and delay-limited information. *IEEE Trans. Inf. Th.*, accepted 2009.
 - [47] G. Lechner, I. Land, and L. Rasmussen. Decoding of LDPC codes with binary vector messages and scalable complexity. In *Proc. 5th International Symposium on Turbo Codes and Related Topics, Lausanne, Switzerland, 2008*.
 - [48] G. Lechner and C. Weidmann. Optimization of binary LDPC codes for the q-ary symmetric channel with moderate q. In *Proc. 5th International Symposium on Turbo Codes and Related Topics, Lausanne, Switzerland, 2008*.
 - [49] P. Luethi, C. Studer, S. Duetsch, E. Zraggen, H. Kaeslin, N. Felber, and W. Fichtner. Gram-Schmidt-based QR decomposition for MIMO detection: VLSI implementation and comparison. In *IEEE Asia Pacific Conf. on Circuits and Systems*, pages 830–833, Macao, China, November 2008.

- [50] P. Luethi, M. Wenk, T. Koch, M. Lerjen, N. Felber, and W. Fichtner. Multi-user MIMO testbed. In *ACM MobiCom'08 / WiNTECH'08 Workshop*, pages 109–110, San Francisco, CA, USA, September 2008. [25](#)
- [51] L. Luzzi, G. Rekaya-Ben Othman, J.-C. Belfiore, and E. Viterbo. Golden code, reed-solomon codes, space-time block codes. In *Proc. Inf. Theory Workshop 2008*, Porto, Portugal, May 2008.
- [52] L. Luzzi, G. Rekaya-Ben Othman, J.-C. Belfiore, and E. Viterbo. Golden code, reed-solomon codes, space-time block codes. *IEEE Trans. Inf. Th.*, submitted 2008.
- [53] S. Mayrargue (Cluster Manager). Broadband Air Interfaces (BAI) cluster. <http://bai.av.it.pt>. [31](#)
- [54] G. Matz. Vector perturbation precoding revisited. In *Joint Workshop on Coding and Communications (JWCC 2008)*, St. Helena (CA), USA, October 2008.
- [55] J. Maurer, J. Jaldén, and G. Matz. Transmit outage precoding with imperfect channel state information under an instantaneous power constraint. In *Proceedings of the IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2008)*, Recife, Brazil, July 2008.
- [56] J. Maurer, J. Jaldén, and G. Matz. Multi-threshold TOP — Full-diversity vector perturbation precoding with finite-rate feedforward. In *Asilomar Conference on Signals, Systems and Computers*, Pacific Grove (CA), USA, October 2009.
- [57] J. Maurer, J. Jaldén, D. Seethaler, and G. Matz. Achieving a continuous diversity-complexity tradeoff in wireless MIMO systems via pre-equalized sphere-decoding. *IEEE Journal for Selected Topics in Signal Processing (JSTSP)*, submitted 2008.
- [58] J. Maurer, J. Jaldén, D. Seethaler, and G. Matz. Vector perturbation precoding for receivers with limited dynamic range. In *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Taipei (Taiwan, R.O.C.), to be published April 2009.
- [59] C. F. Mecklenbräuker, A. Paier, T. Zemen, G. Matz, and A. F. Molisch. On the temporal evolution of signal subspaces in vehicular MIMO channels in the 5 GHz band. In *Joint Workshop on Coding and Communications (JWCC 2008)*, St. Helena (CA), USA, October 2008.

- [60] Members of the MASCOT consortium. Multiple Access Space–Time Coding Testbed (MASCOT), Annex I (v. 2005-10-13), Description of Work, Contract no. 26905, October 13 2005. [20](#), [27](#), [28](#), [30](#), [35](#)
- [61] Members of the MASCOT consortium. Multiple Access Space–Time Coding Testbed (MASCOT), Annex I Amendment 1 (v. 2006-11-30), Description of Work, Contract no. 26905, November 30 2006. [20](#), [30](#)
- [62] Members of the MASCOT consortium. Multiple Access Space–Time Coding Testbed (MASCOT), Annex I Amendment 2 (v. 2008-10-18), Description of Work, Contract no. 26905, October 18 2008. [20](#), [30](#)
- [63] C. Novak, F. Hlawatsch, and G. Matz. Low-complexity factor graph receivers for spectrally efficient MIMO-IDMA. In *Proc. IEEE ICC 2008*, Beijing, China, 2008.
- [64] C. Novak, G. Lechner, and G. Matz. MIMO-BICM with imperfect channel state information: EXIT chart analysis and LDPC code design. In *Asilomar Conference on Signals, Systems and Computers*, Pacific Grove (CA), USA, October 2009.
- [65] C. Novak, G. Matz, and F. Hlawatsch. A factor graph approach to joint data detection and channel estimation in pilot-assisted IDMA transmissions. In *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Las Vegas (NV), USA, April 2008.
- [66] C. Novak, G. Matz, and F. Hlawatsch. Factor graph based design of an OFDM-IDMA receiver performing joint data detection, channel estimation, and channel length selection. In *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Taipei (Taiwan, R.O.C.), to be published April 2009.
- [67] T. J. Oechtering and H. Boche. Optimal time-division for bidirectional relaying using superposition encoding. *IEEE Communications Letters*, 12(4):265–267, April 2008.
- [68] E. Riegler and G. Taricco. Asymptotic ergodic capacity region and rate optimization of a multiple access OFDM-MIMO channel with separately-correlated Rician fading. In *Proc. IEEE Globecom*, New Orleans (LA), USA, Nov. 30–Dec. 4 2008. [19](#)
- [69] E. Riegler and G. Taricco. Asymptotic statistics of the mutual information for spatially-correlated Rician fading MIMO channels with interference. *IEEE Trans. Inf. Th.*, submitted 2008.

- [70] S. Schwandter, P. Fertl, C. Novak, and G. Matz. Log-likelihood ratio clipping in MIMO-BICM systems: information geometric analysis and impact on system capacity. In *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Taipei (Taiwan, R.O.C.), to be published April 2009.
- [71] D. Seethaler and H. Bölcskei. Infinity-norm sphere-decoding. In *IEEE Int. Symposium on Information Theory (ISIT)*, July 2008.
- [72] M. Shafi, H. Huang, A. Hottinen, P.J. Smith, R.A. Valenzuela, and L.J. Cimini. Guest editorial: Mimo systems and applications: Field experience, practical aspects, limitations and challenges. *IEEE J. Sel. Areas Comm.*, 26(6):841–844, August 2008.
- [73] S. Shi, M. Schubert, and H. Boche. Rate optimization for multiuser mimo systems with linear processing. *IEEE Trans. Sign. Proc.*, 56(8):4020–4030, August 2008.
- [74] C. Studer, A. Burg, and H. Bölcskei. Soft-output sphere decoding: algorithms and VLSI implementation. *IEEE Journal on Selected Areas in Communications*, 26(2):290–300, February 2008.
- [75] C. Studer, P. Luethi, and W. Fichtner. VLSI architecture for data-reduced steering matrix feedback in MIMO systems. In *IEEE Int. Symp. on Circuits and Systems*, pages 300–303, Seattle, WA, USA, May 2008.
- [76] C. Studer, D. Seethaler, and H. Bölcskei. Finite lattice-size effects in MIMO decoding. In *Proc. Asilomar Conference on Signals, Systems, and Communications*, Pacific Grove (CA), USA, October 2008.
- [77] G. Taricco. Asymptotic mutual information statistics of separately correlated Rician fading MIMO channels. *IEEE Trans. Inform. Theory*, 54(8):3490–3504, August 2008.
- [78] G. Taricco. Asymptotic error performance of space-time codes over fully correlated Rician fading MIMO channels with imperfect CSI. In *IEEE ICASSP 2008*, Las Vegas (NV), USA, to be published in 2008.
- [79] G. Taricco and E. Riegler. Asymptotic ergodic capacity of wideband MIMO channels with separately-correlated Rician fading. In *Proc. IEEE Globecom*, New Orleans (LA), USA, Nov. 30–Dec. 4 2008. 19
- [80] G. Taricco and E. Riegler. On the ergodic capacity of correlated Rician fading MIMO channels with interference. *IEEE Trans. Inf. Th.*, submitted 2008.

- [81] G. Taricco and Erwin Riegler. Ergodic capacity of wideband MIMO channels. In *Joint Workshop on Coding and Communications (JWCC 2008)*, St. Helena (CA), USA, Oct. 26–28 2008. (invited).
- [82] G. Tauböck and F. Hlawatsch. A compressed sensing technique for OFDM channel estimation in mobile environments: Exploiting channel sparsity for reducing pilots. In *in Proc. IEEE ICASSP-2008*, Las Vegas (NV), USA, March–April 2008.
- [83] R. Tresch and M. Guillaud. SINR estimation in random beamforming with noisy MIMO channel measurements. In *IEEE ICC 2008*, Beijing, China, May 19–23 2008.
- [84] R. Tresch and M. Guillaud. Cellular interference alignment with imperfect channel knowledge. In *Proc. IEEE International Conference on Communications (ICC)*, submitted 2009.
- [85] E. Viterbo. Irregular sampling and random matrix theory. In *Joint Workshop on Coding and Communications (JWCC 2008)*, St. Helena (CA), USA, October 2008.
- [86] E. Viterbo and A. Hottinen. Optimal user pairing for multiuser mimo. In *Proc. IEEE Internat. Symp. on Spread Spectrum Techniques and Applications (ISSSTA)*, Bologna, Italy, August 2008.
- [87] N. Vucic and H. Boche. Downlink precoding for multiuser MISO systems with imperfect channel knowledge. In *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2008)*, Las Vegas, USA, April 2008.
- [88] N. Vucic and H. Boche. Probabilistically constrained robust power allocation in multiuser miso systems. In *Proc. Asilomar Conference on Signals, Systems, and Communications*, Pacific Grove (CA), USA, October 2008.
- [89] N. Vucic and H. Boche. Robust Transceiver Optimization for Frequency Selective MIMO Channels. In *Proc. 9th IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2008)*, Recife, Brazil, July 2008.
- [90] N. Vucic and H. Boche. A tractable method for chance-constrained power control in downlink multiuser MISO systems with channel uncertainty. *IEEE Signal Processing Letters*, 2008. accepted.

- [91] N. Vucic and H. Boche. Robust QoS-constrained optimization of downlink multiuser MISO systems. *IEEE Transactions on Signal Processing*, 57(2):714–725, February 2009.
- [92] N. Vucic, H. Boche, and S. Shi. Robust transceiver optimization in downlink multiuser MIMO systems. *IEEE Transactions on Signal Processing*, 2008. submitted.
- [93] N. Vucic, H. Boche, and S. Shi. Robust transceiver optimization in downlink multiuser MIMO systems with channel uncertainty. In *Proc. IEEE International Conference on Communications (ICC 2008)*, Beijing, China, May 2008.