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This revised final report reviews the third reporting period (1.1.2008—28.02.2009). Further, it gives an overview over the achievements and conclusions of the whole project and reflects the reviewers' recommendations during the final technical review. 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 is that every comprehensive capacity region can be expressed as a sub-level set of an interference function. This enables a general framework for analyzing performance trade-offs in multiuser networks.

The most promising techniques for MIMO/MU-MIMO implementation in future mobile networks are those which gracefully trade throughput against processing delay. Iterative algorithms for soft interference cancellation are very relevant. The sorted QR decomposition and lattice-reduction are relevant for various promising MIMO/MU-MIMO techniques. The sphere decoder's sensitivity to transmit side RF impairments needs further study. Very promising is relaying for nodes with multiple antennas.

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Executive Summary

This deliverable reviews the third reporting period of the MASCOT project in detail and discusses the project's overall achievements.

- Detailed review of third reporting period
    - Research progress during 2008–2009 in WP1, WP2, and WP3.
    - Dissemination activities during 2008–2009.
    - Consortium and IPR management.
- Overall achievements
    - Key issues: Answering the ten questions
    - Deliverable D1.3.2
    - Deliverable D2.2.1
    - Deliverable D3.1.3
    - Deliverable D3.2.2

Chapter 1

Research Progress during 2008–2009

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 between 1.1.2008 and 28.02.2009.

1. During 2007, the research in WP1 dealt with MU-MIMO resource allocation (the focus being scheduling and resource allocation with proportional fairness), with space-time codes (with a focus on MIMO multiple access and concatenated schemes), and with MIMO transceiver schemes (with emphasis on receivers with incomplete information about number of users and channel states as well as computationally efficient algorithms for detection and precoding). A key result are the baseband algorithms summarized in deliverable D1.3.1, some of which are hot candidates for VHDL implementation during year 3.

2. WP2 focused mainly on the composition of the MASCOT VHDL reference design library, the testing and reporting of the MIMO Medium Access Control (MAC) algorithms of the MASCOT real-time testbed, the extension of the MASCOT real-time testbed with a sorted QR decomposition (SQRD) ASIC for MIMO preprocessing, and various enhancements of the offline testbed to run single- and multi-user MIMO experiments with flexible configuration settings. Key results are Deliverable D2.2.1 (“VHDL Library of Reference Designs”) and Deliverable D2.3.2b (“Report on testing of MIMO MAC algorithms”).

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 result from WP3 is the insight 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.

1.1 Workpackage 1

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

Task 1.1

Contributions within this task have been provded 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 besolved 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 multiples 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 o 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 Programming (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. One the one hand, sphere decoding (SD) approaches for soft detection were investigated where significant complexity reduction was achieved by using smart tee 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 studied 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.

1.2 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.

1.3 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 [167].

- 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 [139].

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

Deliverables: In the original project plan [121, 122], there were no deliverables foreseen during the third reporting period. However, for Amendment 2 [123], 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.

1.4 Workpackage 4

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

1.4.1 Web-site

The public web-site [60] is continuously updated. Here, the project announces events, tutorials, special sessions, publications, deliverables, and achievements.

`http://www.ist-mascot.org`

1.4.2 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 Mecklenbräuker (FTW). Around 30 manuscripts were submitted in total for publication in September 2008 and are currently being reviewed. Further information is available online[1].

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".

1.4.3 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` .

1.4.4 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

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

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

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1.4.5 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/`

1.4.6 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 [12, 23, 64] 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 codes[2] whereas the second evaluates the MU-MIMO performance of specific low-complexity receivers by measurements[3].

1.4.7 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* [105] 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)

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

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

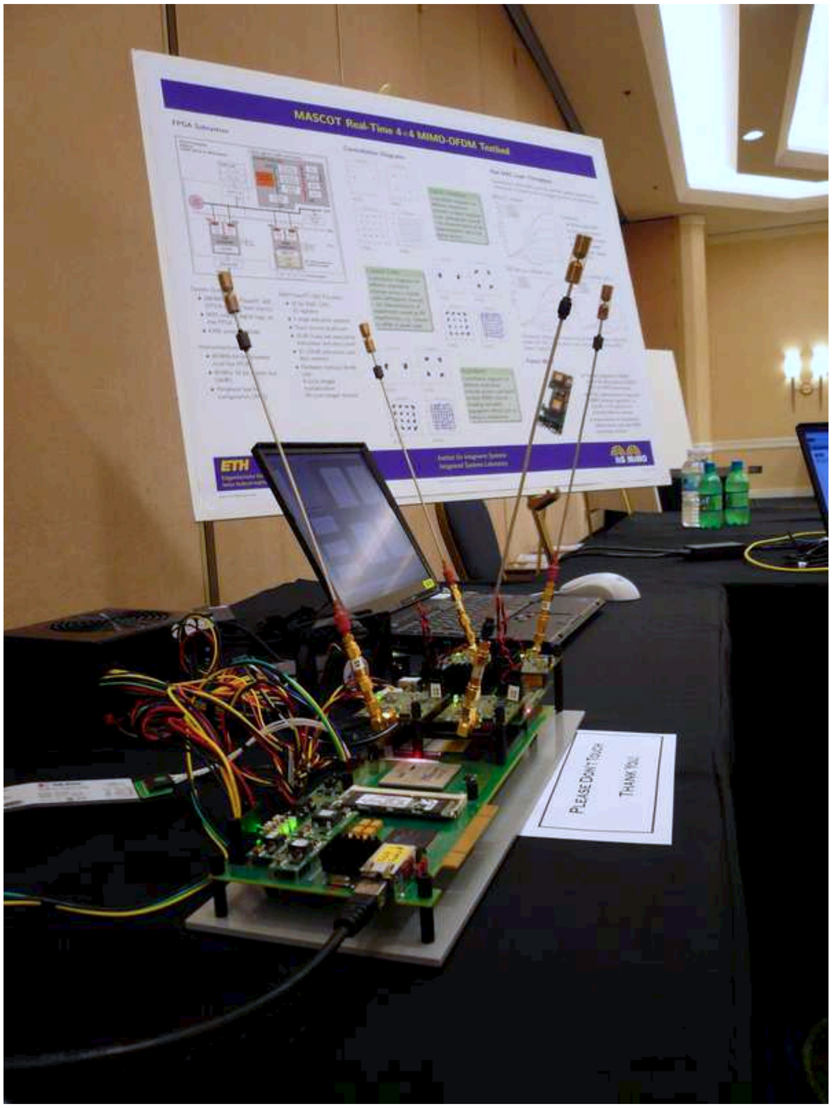

Figure 1.1: Multi-User MIMO Testbed at WinTech'08 Demo Contest, San Francisco, Sep. 19, 2008

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`

1.4.8 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`

new text:

1.4.9 Contributions to standardisation

In the context of a bilateral cooperation between FhG-HHI and Siemens (today: Nokia Siemens Networks), some MASCOT research results on interference 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 be the partners NOKIA, UNICAL, VUT, and FTW and the results were published at the ITG/IEEE Workshop on Smart Antennas (WSA 2007) [92].

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.

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[4] 3GPP TSG RAN WG1 LTE ad hoc, R1–061899, Interference minimization and cancellation techniques for MIMO systems, Cannes, France, Jun. 27–30, 2006.

[5] 3GPP TSG RAN WG1 LTE ad hoc, R1–062301, Optimum combination of interference coordination and cancellation, Talinn, Estonia, Aug. 28–Sep. 1, 2006.

[6] 3GPP TSG RAN WG1 LTE ad hoc, R1–063245, Performance considerations for unitary versus non-unitary precoding, Riga, Latvia, Nov. 6–10, 2006.

1.4.10 Exploitation activities

Intellectual Property Right management

The project partners established an IPR Policy Committee consisting of technical experts and legal experts in September, 2006[7]. 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 filing[8] 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 portfolio[9].

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, this library may be commercially licensed to industry[10] and academic institutions. 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 1.1) 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 Piemont. 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.

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[7] see Technical Annex (Description of Work): [121], Section 6.2.2, page 19.

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

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

[10] see Technical Annex [121], 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 1.1: Technology transfer institutions which will aid in exploitation, especially concerning the licensing of the VHDL reference designs.

1.4.11 Future use of the MU-MIMO testbed

Future use of the real-time MU-MIMO testbed. Our testbed activities in the near future are focused on resolving the discrepancies between the expected and the actual performance. To this end we are currently investigating the measurement issues that appear to distort some of our measurement results. Once these issues have been resolved more effort will be spent on the identification of the sources of the observed implementation loss in the real-time testbed. A more mid-term objective is to remove the synchronization cables between the terminals of the MU-MIMO testbed. To this end, we are currently implementing a pre-compensation stage for the frequency offset in the real-time testbed transmitter. The necessary MAC layer extensions to allow for timing and frequency-offset synchronization between the terminals will follow as a next step.

Apart from these developments, the testbed will continue to serve as a technology demonstrator. In particular, we will demonstrate the testbed at the ISCAS 2009 conference where the corresponding paper has been nominated as a candidate for the Student Best Paper Award.

Future use of the offline MU-MIMO testbed. The offline testbed will serve theree purposes: First, it will be used for further studies of MU-MIMO algorithms. In particular, we intend to implement and demonstrate the vector-perturbation precoding algorithms developed in MASCOT [112] on the offline testbed. This implementation will be done in collaboration between VUT and ETHZ. The second application of the offline testbed is to perform a more in-depth analysis of the different RF impairments, with a focus on transmit-side impairments that can cause a significant performance loss for ML detectors. Finally, in the long term, the offline testbed will serve as a basis for future MIMO testbed research at ETHZ. An area of particular interest for such efforts are relay networks.

Chapter 2

Overall achievements of the Project

2.1 Deliverables

All deliverables of the project can be accessed online via the following link http://www.ist-mascot.org/deliverables

2.2 Patents

The IPRs generated by the project are evaluated by the IPR Policy Committee for patent filing or for exploitation. The actual patent filing itself is performed by the partners involved.

- During 2006 there were no patent applications.
- During 2007 there were three (3) patent applications (all applications by Nokia).
- During 2008 there were four (4) patent applications (all applications by Nokia).
- During 2009 there is one (1) patent application (all applications by Nokia).

Chapter 3

Key Issues

In 2005, we formulated ten questions to be addressed by the MASCOT project (see Section 2.3 of [121]). These questions are relevant to a variety of wireless systems employing MIMO techniques, such as high-speed WLANs (IEEE 802.11n, including the ad-hoc mode), mobile cellular systems (3GPP Long Term Evolution), and BWA systems (IEEE 802.16). The overall objective of MASCOT is to answer these questions without focusing on a single system or standard. We believe that advances on the integration of MU-MIMO technology into wireless systems require these answers.

In the following, we will address these questions one by one.

3.1 What is the system capacity?

The capacity of a MIMO communication system depends on the number of users, on the number of antennas, on the noise level, on the channel bandwidth, on the type of scattering (presence or absence of a line-of-sight component), and on the spatial correlation. Within MASCOT, several works addressed the issue of evaluating the system capacity. A preliminary assessment of the properties that must be satisfied by the optimum capacity achieving covariance matrix was given in [134]. The analytic complexity of this approach prevented however to apply it in many cases of interest, so that, subsequently, it was realized that different approaches could be followed, such as the *replica method*. Using the replica method, capacity could be well approximated in a very large number of situations of interest. This method allowed to find approximations to the system capacity when the number of antennas grows asymptotically large. In spite of being an asymptotic method, numerical results show that it can be applied successfully even when the number of antennas is finite, and even small (as small as a few units!).

The first paper using this approach capacity was [160]. Here, capacity was obtained in the absence of channel state or distribution information at the transmitter (which leads to uniform transmit power allocation). This MASCOT paper solved the outstanding problem of finding the mean and the variance of a separately correlated Rician fading MIMO channel. This paper, presented in the IEEE Globecom 2006, was subsequently expanded and led to the journal paper [162] which also showed the asymptotic Gaussian nature of the capacity itself. Several other MASCOT papers have been published dealing with the presence of interference and aimed at finding the capacity under the assumption of available channel distribution information at the transmitter [166, 168, 137, 138, 140].

Further studies extended the previous analysis of the system capacity to the multiuser scenario and to the case of wideband (OFDM based) MIMO systems [139, 169, 167].

The following numerical example is extracted from [139]: let the system capacity be the sum rate that is achievable by a two-user MIMO system, where each user is equipped with 4 antennas, with a mild line-of-sight component (Rician factor of 0 dB), exponential power delay profile over three symbols, and heavy spatial correlation. Then, with optimum power allocation, we have a system capacity of 8.3,11.7,16.1,21.4,27.2 bit/s/Hz at 5,10,15,20,25 dB of user SNR, respectively. Under the same assumptions, but with uniform (suboptimum) power allocation, the system capacity would reduce to 6.2,9.8,14.4,20.0,26.4 bit/s/Hz, respectively.

3.2 What are the user capacity and link reliability?

Analysis of capacity for MIMO fading channels is a difficult task and can be managed by an asymptotic (in the number of antennas) approach using the replica method [160, 162]. A set of achievable rates for the individual users in a MIMO multiple access system corresponds to a certain point in a capacity region. The boundary points of the capacity region are achieved by optimizing the covariance matrices of the individual users. In the MASCOT papers [166, 168] we derived an algorithm which efficiently computes the optimum covariance matrix of a single user regarding all other users as interference. An arbitrary boundary point in the capacity region can be obtained by weighted rate sum optimization. The corresponding optimum covariance matrices are obtained by iteratively solving coupled systems of fixed point equations and a convex optimization problem. These algorithms have been obtained in the MASCOT paper [139] for the wideband case, assuming a channel model which is sufficiently general enough to allow for considering different spatial correlation matrices for each user and delay at the transmitter and the receiver as well as line of sight components. In the special case where one maximizes the sum rate (system capacity), the convex optimization problem reduces to the well known water filling procedure for the eigenvalues of the optimum covariance matrices.

3.3 How many users can be supported reliably?

The work within Task 1.1 revealed that appropriate MIMO scheduling allows to exploit significant spatial and multi-user diversity (see deliverable D1.1.1). Different resource allocation strategies were investigated, aiming at a good tradeoff between user fairness and system efficiency. The analysis of the achievable quality-of-service (QoS) region in Task 3.1 provided a thorough understanding of the interactions between the users. QoS values within the region can be simultaneously supported. A max-min indicator function for "supportability" was derived.

The joint multi-user space-time code designs developed within Task 1.2 allow to enter rate regions that otherwise can only be realized using a larger number of receive antennas (see D1.2.1). Hence, these multi-user space-time code designs are crucial when it comes to simulatenously supporting many high-rate users (both in the uplink and the downlink).

Whether a certain number of users can be reliably supported also depends on the receiver processing. Advanced receiver algorithms (specifically data detection) is crucial to be able to exploit multiplexing and diversity gains. Specifically, we found that identical performance can be obtained using either computationally expensive data detection with the minimum number of receive antennas or low-complexity detectors in conjunction with increased number of receive antennas.

MIMO precoding using channel inversion and vector perturbation at the base station (access point), possibly combined with advanced user scheduling, is a particularly attractive scheme to support large numbers of users, specifically in the donwlink of cellular networks. Here, most of the computational complexity is shifted to the base station, whereas the terminals require very little processing power. Furthermore, the scheme is transparent in the sense that the individual terminals are completely decoupled from the number of users present in the system.

In Task 1.3 we have developed iterative algorithms for max-min balancing and QoS-constrained power minimization. The algorithms are able to detect infeasible scenarios, where QoS targets of several users cannot be supported. Specifically, we have studied data rates and minimum mean square error targets, including adaptive receive and transmit MIMO filtering.

3.4 What are the coverage improvements?

MU-MIMO techniques can provide increased diversity gain translating to reduced outage probabilities which increases the coverage area without increasing transmit power. However, increasing the diversity order needs to be traded against available sum-rate of any MU-MIMO wireless system. Therefore, the MU-MIMO coverage and capacity analyses can no longer be considered separately.

Additionally, MU-MIMO techniques provide a *cluster gain*, rather than just a performance gain limited to the a single serving cell or sector. This means that a single cell or sector equipped with MU-MIMO algorithms will not just improve the coverage and capacity of the single cell, but will additionally improve the coverage and capacity of the neighbouring cells, due to the reduced intercell interference level. With the advent of WiMax and 3GPP Long Term Evolution, aspects of interference alignment become increasingly important.

3.5 What must be altered in the existing cellular infrastructure?

MIMO is already an inherent part of several wireless standards. Most recently, it has been defined to 3GPP Long-Term Evolution on top of OFDMA in downlink and enablers for virtual MIMO in uplink. WiMAX (IEEE 802.16e/m) is another major cellular standard where MIMO plays a central role. These systems support various space-time codes (orthogonal and non-orthogonal) and also more conventional multi-streaming with horizontal or vertical coding. While these specifications support MIMO, its successful real-world deployment is not trivial. Cellular systems have also other means for increasing system throughput, such as channel-aware scheduling and automatic repeat request. MIMO, if used to increase diversity, reduces the gains due to channel-aware scheduling. Therefore, the resource allocation mechanisms and their enablers (such as feedback from user equipment) must be tuned to reap the best of both worlds. This has already led to rapid increase of feedback channel rates in aforementioned systems and additional work in reducing the feedback load may be beneficial (to reduce cost of overhead). With scheduled or feedback MIMO, MIMO transmission (such as space-time codes and multi-streaming) is viewed as a modulation method. A suitable (MIMO) modulation method is selected for each channel realization using Channel Quality Indicator (CQI) signalling. In this approach MIMO will give benefits (as MIMO is not used if not deemed beneficial or if channel does not support it). The game is different when considering broadcast services (such as DVB,DVB-H). There, feedback is essentially lacking and any additional diversity is most welcome. For MIMO, this application suggests the use of MIMO over multiple transmitting stations (cooperative-MIMO). Generally, the network needs to be synchronized in C-MIMO applications.

In summary, point-to-point MIMO is already adopted in cellular standards and there are various supporting functions for that (control signalling, pilot definitions etc). Multiuser MIMO is still under development, and network (or C-MIMO) likewise. The latter variants of MIMO require extensive studies with respect to requirements of user or network synchronization. From a practical viewpoint, also the MIMO transmission methods need to be defined so that they can be received with sufficiently simple receiver. Only if the MIMO gains with a simple receiver are significant are large-scale MIMO deployments sensible.

3.6 Can MU-MIMO be implemented in a practical system?

The key to achieve the full potential of MU-MIMO communications are the availability of optimum maximum-likelihood (ML) or quasi-ML MU-MIMO detection algorithms, which, from a physical-layer computational complexity perspective, turned out to be the limiting factor in terms of number of antennas and simultaneously transmitting users. This also holds for the various multiuser space-time codes that have been proposed in the MASCOT project. Hence, for MU-MIMO communications efficient detection algorithms are of utmost importance. In the course of the MASCOT project, various efficient ML and suboptimum detectors have been proposed and analyzed with respect to performance and suitability for VLSI implementation. In particular, this includes approaches based on sphere decoding [53, 55, 155, 188] and lattice-reduction [188, 98, 48, 43]. For MU-MIMO systems with system parameters similar to common wireless standards (such as WiMAX, WiFi, and 3GPP Long Term Evolution), the research within the MASCOT project has demonstrated that ML detection (hard and soft sphere decoding) can be implemented economicly up to 8 (real-valued) dimensions [53, 55, 155]. This would, for example, limit MU-MIMO communications with optimum detection to two simultaneously transmitting users each employing two transmit antennas. If more users have to be supported, one has to resort to suboptimum MU-MIMO detectors [188, 48, 43].

3.7 How flexible and scalable are MU-MIMO networks?

In workpackage 3 we have developed a generic framework for modeling interactions between multiple users in a wireless network. This so-called *interference calculus* is based on a small set of core properties of interference-coupled MU-MIMO wireless networks, independent of their size and specific system layout. It therefore aims at maximum flexibility and scalability. Within the interference-calculus framework, we have derived various resource allocation algorithms in workpackage 1, taking into accout more specific assumptions on the system parameters. Among the investigated system designs are convex and log-convex interference functions arising from robust signal processing techniques. We have also studied concave interference functions resulting from adaptive receive or transmit strategies.

3.8 Can we upgrade current standards to MU-MIMO?

Current wireless systems been recently (during MASCOT lifespan) upgraded to support variants of MU-MIMO. In particular, both in 3GPP and IEEE 802.16e the respective specifications support assigning reference signal sequences to users in uplink so that (at least) two users can be transmitting in the same time-frequency slot (See 3GPP TS36.211 Chapter 5.5.2.1.1 and Collaborative Spatial Multiplexing in IEEE 802.16e). This is a necessary requirement for MU-MIMO. How to use this possibility in practice is an implementation issue. In practical implementation, one needs to decide which two users can coexist in the same time-frequency slot. This is one problem that ongoing MASCOT work has tried to answer, see Deliverable 3.2.2. MASCOT work has also contributed to the design of multiuser space- time codes and transmit precoding issues. These are currently not in current wireless systems. However, form standardization viewpoint, multi-user space-time codes could be embedded to systems rather easily (i.e. no direct external effects to other users - such effects hinder standardization suceess typically). Like for all other things, successful standardization would require extensive system simulations with clear benefits.

To summarize, multi-user MIMO is already becoming a reality in terms of standardization, but practical implementations of it are scarce. From practical viepoint, Nokia Siemens Networks[1] and Nortel[2] have demonstrated pilot systems recently.

On the other hand, the benefit of MU-MIMO in practice depends on prevailing system assumptions and system constraints. MASCOT testbed developed within workpackage 2 is based on the IEEE 802.11 standard. The work on the testbed unveiled that the addition of simultaneous multi-user capabilities to the IEEE 802.11 standard is associated with a significant effort in the PHY layer as well as in the MAC layer (e.g., user synchronization, protocol overhead, backward compatibility). Therefore, it is unlikely that simultaneous multiuser capabilities will become part of future IEEE 802.11 standard , at least in the near future. Moreover, the 802.11 protocol complexity and backward compatibility aspects hinder efficient realization of multi-user capabilities. Due to these reasons, the theoretical MU-MIMO gains cannot necessarily be realized in practice in IEEE 802.11n.

3.9 Under what channel conditions are MIMO gains realisable?

In practice, MIMO systems suffer from spatial correlation which often prohibits the transmission of parallel data streams. However, one very effective method for decorrelating antennas is to use different polarization for transmitting two data streams. As has been shown in Ref.[3] even in a worst case line-of-sight scenario significant MIMO gains can be achieved. If polarization diversity cannot be used or if more than two transmit antennas shall be employed, one can always use precoding or beamforming to increase the receive signal power (see Ref. [4]). As a result, also the data throughput is increased. At the receiver side, multiple antennas are *always* beneficial since an array

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[1] `http://www.nsn.com/global/Press/Press+releases/news-archive/Researchers_at_Nokia_Siemens_Networks_double_the_capacity.htm`

[2] `http://www2.nortel.com/go/news_detail.jsp?cat_id=-8055&oid=100207918&locale=en-US`

[3] C. Mehlführer, S. Caban and M. Wrulich, M. Rupp: Joint Throughput Optimized CQI and Precoding Weight Calculation for MIMO HSDPA, in Proc. 42nd Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, Oct. 2008

[4] C. Mehlführer, S. Caban, M. Rupp: Physical Layer Throughput Measurements of MIMO HSDPA, to be submitted 2009.

gain can be exploited.

From a theoretical point of view, the effect of channel conditions on the ergodic capacity of a MIMO system with interference has been studied in the MASCOT paper [168]. Besides the effect of the signal-to-noise ratio and the signal-to-interference ratio, we also analyzed the effect of spatial correlation, of the Rician factor, and of the angle of arrival of the interference. We noticed that the effect of increasing spatial correlation is quite unpredictable when the signal-to-interference ratio is low whereas it provides the expected results when the signal-to-interference ratio is high (capacity decreasing with correlation). For fixed signal-to-noise ratio and fixed signal-to-interference ratio decreasing the level of scattering, i.e. increasing the Rician factor, decreases capacity. The following numerical example is extracted from [168] and confirms that MIMO gains are realisable also for strong line-of-sight components: for a two-user MIMO system with a Rician factor of 10 dB and without spatial correlation, a signal-to-noise ratio of 0dB, and a signal-to-interference ratio of -10dB, we achieve a capacity of 0.14, 0.39, 0.60, 0.79, 0.96 bit/s/Hz if the number of transmit, receive, and interfering antennas is equal to 1, 2, 3, 4, 5, respectively.

3.10 What is the optimal antenna array configuration?

Admittedly, this is a largely open question for MIMO networks and it seems that it cannot be answered simply. The optimal antenna configuration for maximum network throughput is very site-specific. A key problem of network planning for MIMO systems is a lack of available MIMO propagation models, which can be used for predicting the signal field strength jointly with the number of available dimensions in the signal space for specific sites. In contrast, propagation models for single antenna transmission and reception can be considered mature. In today's standard radio network planning tools, the propagation model for scalar channels consists of a basic pathloss model, line-of-sight checking, and corrections for topography, morphography, and street orientation. Propagation models for MIMO transmission are much less understood, but the recently developed model within COST 273 which is currently further developed within COST 2100 carries great promise.

Automated design optimization tools in combination with advanced radio technologies are currently developed and used for 3GPP Long Term Evolution radio network planning and design. These tools compute the minimum resources required to satisfy coverage/quality/capacity requirements. Simultaneously, design optimization finds the best antenna array configuration for each site/sector as well as the best strategy to introduce advanced radio technologies. By doing so, such tools boost the overall network performance. The more efficient use of the infrastructure results in fewer base stations for the same performance, compared to a manual design.

Chapter 4

SWOT Analysis of Sphere Decoding

4.1 Preliminaries

Sphere decoding (SD) is a technique which implements near maximum likelihood (ML) detection with a complexity that is on average far below an exhaustive search. The underlying idea of the algorithm can be modified in various ways, e.g. for computing log-likelihood ratios for a subsequent channel decoder or for implementing iterative detection and decoding. Moreover, several flavors of sphere decoding have been developed which realize various tradeoffs between complexity and performance. The original algorithm can be adjusted to various implementation constraints (e.g., latency or the need to achieve constant throughput). In the subsequent summary, we consider the entire class of SD algorithms rather than a specific implementation and we attempt to provide a set of general qualitative conclusions that can guide the quantitative considerations when analyzing a specific communication system.

4.2 SWOT Analysis

A summary of the SWOT analysis for sphere decoding in multi-user MIMO communications is provided in Fig. 4.1. A more detailed discussion of the issues summarized in the figure is provided in the following.

Strengths The main advantages and strengths of sphere decoding and related decoding techniques over other multi-user and MIMO detection strategies can be summarized as follows:

Strengths ▪ Optimum performance under ideal conditions ▪ Robustness against varying channel conditions and antenna correlation ▪ Design-time complexity/ performance tradeoffs ▪ Runtime scalability	**Weaknesses** ▪ Very sensitive to transmit-RF impairments ▪ Economic application is limited to few, yet most relevant, system configurations ▪ Considerable additional area compared to non-iterative linear receivers
Opportunities ▪ Impact of transmit-RF impairments can be mitigated ▪ Iterative detection and decoding limited by latency constraints ▪ Iterations multiply the area of the MIMO detector and the channel decoder	**Threats** ▪ Linear receivers with asymmetric antenna configurations ▪ Iterative detection and decoding ▪ Iterative linear MIMO detection with parallel interference cancellation

Figure 4.1: SWOT analysis for sphere decoding

Optimum performance under ideal conditions: In the absence of almost any implementation constraints, sphere decoding can be employed to achieve either optimum or at least very close to optimum performance for a wide range of system configurations. With proper modifications of the basic algorithm, hard-output and soft-output MIMO detection can be realized and even soft-input soft-output MIMO detection can be implemented in iterative receiver configurations. In all cases, the complexity is far below an exhaustive search and within the reach of modern process technologies.

Robustness against varying channel conditions and spatial correlation: In MIMO-OFDM systems with linear receivers, frequency diversity can partially compensate for a lack of spatial diversity, allegedly closing the gap between linear and close-to optimum MIMO detectors. However, the need for significant frequency diversity also leads to lack of robustness against varying channel conditions, which, in a mostly static environment, translates into poor coverage.

Moreover, the error rate performance of linear receivers is severely degraded by strong antenna correlation. The latter appears especially in highly integrated devices for which the possible antenna spacing is severely limited. Simulations show that sphere decoding is much more robust against spatial correlation and thus much better suited for such small devices.

Design-time complexity/performance tradeoff: Sphere decoding is an iterative algorithm whose worst-case complexity corresponds to an exhaustive search. In practical implementations, the maximum decoding effort is determined by the communication bandwidth and by the amount of hardware (silicon area) allocated for the MIMO detection process. Since multiple sphere decoder units can work in parallel on subsequent data symbols, the amount of area and thus the complexity/performance tradeoff can easily be adjusted at design time to meet the desired performance level. In principle adjustments can be made from hard-output successive interference cancellation all the way to an exhaustive search with optimum performance.

Runtime scalability: Many relevant communication standards allow for adaptive modulation and support different communication bandwidths. For a given hardware configuration, sphere decoding always extracts the best possible performance. For example, sphere decoding can spend more effort on each symbol when the communication bandwidth is reduced, resulting in better performance. On the other hand, linear detection can not exploit the reduced symbol rate to provide more reliable operation.

Weaknesses

Sensitivity to transmit-RF impairments: Simulations have shown that MIMO receivers based on sphere decoding suffer severely from transmit-RF non-idealities. In fact, without proper compensation measures, typical error vector magnitudes of 28dB-32dB can degrade the performance of sphere decoding to an extent that it becomes far worse than any linear detector which suffers only insignificantly from these impairments.

Economic application is limited to few system configurations: Sphere decoding is a technique to perform multi-user and MIMO detection with a complexity that is far below an exhaustive search. Nevertheless, the complexity of the algorithm still scales exponentially in the rate and thus also eventually becomes prohibitive for high rates. In practice, for wideband systems (>20MHz) with 64-QAM modulation, sphere decoding is only economically feasible for up to 4-5 spatial streams. Beyond this limit, other suboptimal detection methods must be employed. On the lower end, it turns out that for two spatial streams even a brute-force exhaustive search can also be implemented economically due to the regularity of the algorithm and the excellent numerical properties. Hence, it can be concluded that for wideband systems supporting 64-QAM modulation sphere decoding is currently mostly attractive for 2-4 spatial streams.

Considerable additional area compared to non-iterative linear receivers: Significant progress has been made in the development of low-complexity sphere decoding algorithms and in the design of corresponding hardware-efficient VLSI architectures. Nevertheless, the true silicon complexity of sphere decoding with close to optimal performance for wideband systems with 2-4 spatial streams and 64-QAM modulation can be as much as a factor of 3-10 above a corresponding linear detector implementations, depending on the desired performance gain (design-time complexity/performance tradeoff).

Threats

Linear Receivers with asymmetric antenna configurations: The performance and robustness issues associated with suboptimal (e.g., linear) receivers can partially be mitigated by with additional receive antennas to stabilize the link and to realize an additional array gain. This measure helps to reduce the gap between suboptimal and close-to optimal receivers. However, the requirement for additional receive antennas is also associated with significant costs that can easily exceed the additional cost for a more complex MIMO detector. Furthermore, the required additional space is not always available. Hence, the viability of this pragmatic solution must be carefully evaluated for each specific situation.

Iterative detection and decoding: Iterative detection and decoding with a low-complexity MIMO detector and a strong outer code is an alternative to using a complex close-to-optimum MIMO detector without iterations. Simulations show that with sufficient iterations a similar or better level of performance can be achieved. Moreover, iterative receivers also share the scalability advantage of sphere decoding in a sense that the complexity/performance tradeoff can be adjusted both at design-time and at run-time by either adjusting the amount of hardware to support a certain number of iterations or by exploiting reduced communication bandwidth to perform more iterations, respectively.

Iterative linear MIMO detection with parallel interference cancellation (PIC): Iterative MIMO detection with PIC enables to only perform iterations over the MIMO detector before sending log likelihood ratios to the channel decoder. Excluding the channel decoder from the loop results in significant area savings and partially alleviates latency problems compared to iterative detection and decoding. Nevertheless, a performance improvement over non-iterative linear detection without iterations is still visible and the performance gap to close to optimum MIMO detectors is reduced. Similar to iterative detection and decoding, control over the number of iterations provides run time and compile time scalability.

Opportunities

Impact of transmit-RF impairments can be mitigated: It has been recognized that transmit-RF impairments can have a detrimental effect on the performance of sphere decoding and related MIMO detection algorithms. However, recently means to effectively mitigate the impact of transmit-RF impairments on MIMO detectors based on sphere decoding have also been discovered. Initial solutions are for example based on hardware-efficient implementations of noise-whitening and preliminary estimates of the true silicon complexity of corresponding implementations indicate that the associated area overhead is relatively small. Hence, we conclude that the impact of transmit-RF impairments on sphere decoding is indeed a considerable issue that must be considered, but we also conclude that the appropriate signal processing can be employed to bring that problem under control with acceptable hardware overhead.

Iterative detection and decoding limited by latency constraints: Obviously turbo processing entails a linear increase of the detection and decoding effort with the number of iterations. VLSI implementations must meet this demand by allocating more hardware resources that are arranged either in a pipeline or in parallel. Unfortunately, in iterative detection and decoding, pipelining adds significant latency to the system which is often inacceptable due to higher-layer latency constraints. On the other hand, the amount of parallel processing is limited by data dependencies so that also the achievable speedup and thus the possible number of iterations is limited.

Iterations multiply the area of the MIMO detector and the channel decoder: As explained previously, the complexity increase associated with multiple iterations leads to an increase in silicon area of both channel decoder and MIMO detector that is at least proportional to the number of iterations. Hence, a low number of iterations is desirable, even at the expense of a slightly more complex MIMO detector. Furthermore, it is noted that iterations require both soft-in soft-out MIMO detectors and soft-output channel decoders which are often significantly more complex compared to the corresponding soft-output MIMO detectors and hard-output channel decoders that are required for non-iterative receivers.

Chapter 5

Promising and relevant techniques for MIMO/MU-MIMO

Here we summarise the most promising and relevant techniques for MIMO and MU-MIMO implementation in future wireless networks. We seperately comment on transmission techniques and and receiver algorithms.

5.1 Transmission Techniques

- The *interference function framework* establishes a very promising general approach to solve challenging resource allocation and scheduling problems in MU-MIMO networks.

- *Interleave division multiple access (IDMA)* is a very simple and powerful coding scheme for MU-MIMO systems. At the transmit side, it requires little modification of existing implementations. The main challenge here is the delay-critical implementation of the corresponding iterative receiver.

- Linear or non-linear (e.g. vector perturbation or Tomlinson-Harashima) *transmit-side precoding* is very attractive since it shifts the computational burden from the user terminals to the base station/access points, thereby allowing for MU-MIMO gains without requiring huge modifications of existing user equipment. The critical issue to be solved with this approach is channel state feedback.

- Various *relaying techniques*, specifically with nodes with multiple antennas, have been found to be very promising in terms of coverage increase. The main practical issue with many of these techniques is the channel state information required at the relay nodes.

5.2 Receiver algorithms

The most promising techniques for MIMO and MU-MIMO receiver implementation are those which gracefully trade hardware throughput against processing delay.

- The *sorted QR decomposition* and *lattice reduction methods* are highly relevant channel preprocessing methods, which enable (or at least improve) several MU-MIMO receiver implementations.
- In high-rate MIMO systems with non-iterative receiver processing, the *sphere decoder* is the most promising algorithm. The last obstacle with regard to its practical application is to deal with transmit-side impairments.
- *Linear and (soft) interference cancelation receivers* are excellent robust alternatives to sphere decoding in the low-rate/low-SNR regime, both with regard to performance and complexity.
- *Iterative (turbo) receivers* using simple MU-MIMO detectors (MMSE, SIC) are promising methods perfance-wise. Delay issues caused by the iterative process are the main challenge with this type of schemes.

Chapter 6

Consortium Management

6.1 Project Steering Committee

The current members of the project steering committee (PSC) are [121, 122, 123]:

1. C.F. Mecklenbräuker (FTW)
2. A. Hottinen (NOK)
3. M. Schubert (FhG-HHI)
4. G. Taricco (PoliTo)
5. G. Matz (VUT)
6. H. Bölcskei (ETHZ),
7. E. Biglieri (FBM-UPF)
8. E. Viterbo (UNICAL), since December 1, 2006 (see [122] and below).

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, ETH Zürich, February 13, 2009 (this is still to happen, ofcourse).

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/`

6.2 Liaison between MASCOT and SURFACE

During June 2006, a liaison between the two FP6–IST projects SURFACE [61] and MASCOT [60] was established. Both projects participate in the Broadband Air Interfaces (BAI) cluster which is moderated by Sylvie Mayrargue (CEA–LETI) [108]. 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 analysis[1], 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.

6.3 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.

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

- 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 Mecklenbräuker (FTW) from May 22, 2007 until June 08, 2007.
- 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.

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