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Abstract:

This report reviews Year 2 of the project (1.1.2007—31.12.2007). 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 D1.3.1, some of which are hot candidates for VHDL implementation in WP2. WP2 focused on the MU-MIMO OFDM testbed and the exploration of the design-space for channel matrix preprocessing algorithms. Key results from WP2 are several architectures and ASIC implementations of channel preprocessing algorithms and the extension of the ETHZ MIMO OFDM testbed. 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.

The liaison between the two FP6–IST projects SURFACE and MASCOT stengthened the dissemination activities during 2007.

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Executive Summary

This deliverable reviews the second year of the MASCOT project.

- Research progress in WP1, WP2, and WP3.
- Dissemination activities during 2007.
- Consortium management.

Chapter 1

Research Progress

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 between 1.1.2007 and 31.12.2007.

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 developement and implementation of the MU-MIMO OFDM testbed and the design-space exploration for channel matrix preprocessing algorithms. Key results from WP2 are several architectures and ASIC implementations of channel preprocessing algorithms and the extension of the ETHZ MIMO OFDM testbed.

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 NOK and FhG-HHI.

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

Progress: *QoS region and proportional fair scheduling/resource allocation (FhG-HHI).* The existence of a proportionally fair power allocation for an interference-coupled wireless system has ben investigated with inverse SIR as performance measure is the inverse SIR under the assumption that the interference functions are log-convex. The problem of proportional fairness can be formulated as an infimum over all possible power allocations. Whether or not this infimum exists depends on the coupling between the interference functions. Within MASCOT, necessary and sufficient conditions for the existence of a proportionally fair power allocation have been provided. It turns out that this problem is fully characterized by the combinatorial structure of the interference coupling. There exist a proportionally fair solution if and only if the dependency matrix can be permuted such that it is block-irreducible and its main diagonal is positive.

The problem of resource allocation in an interference-coupled wireless network has been addressed using a framework of network utility optimization that is motivated by fairness and efficiency issues. This is required since in a wireless context, interference between users can result in a complicated structure of the quality-of-service region, depending on power allocation, transceiver signal processing etc. It was shown that for a certain class of log-convex interference functions, the symmetric Nash bargaining game is equivalent to proportional fairness, as introduced by Kelly et.al. This provides a link between the axiomatic framework of interference functions and the bargaining theory (which is also based on axioms). In particular, it turns out that under certain conditions, proportional fair resource allocation can be interpreted as a symmetric Nash bargaining game, with equal user priorities. So besides the classical motivation for proportional fairness (as an alternative to max-min fairness), an additional motivation in terms of bar-

gaining is obtained. This is a step towards a general better understanding of fairness issues in wireless networks.

Iterative power control and resource allocation for general interference functions (FhG-HHI). In a multiuser wireless network, users are coupled by interference. Thus, transmission powers should be optimized jointly with the receive strategy, like beamforming, CDMA, base station assignment, etc. We study the problem of minimizing the total transmission power while maintaining individual QoS values for all users. This problem can be solved by the fixed-point iteration proposed by Yates as well as by a recently proposed matrix-based iteration. It was observed previously by numerical simulations that the matrix-based iteration has interesting numerical properties, and achieves the global optimum in only a few steps. However, an analytical investigation of the convergence behavior has been an open problem so far. During year 2 of MASCOT, it was shown that the matrix-based iteration can be reformulated as a Newton-type iteration of a convex function, which is not continuously differentiable. This property is caused by ambiguous receive strategies, resulting in ambiguous representations of the interference functions. By exploiting the special structure of the problem, the iteration was shown to actually have super-linear convergence.

Subcarrier allocation using linear programming (NOK). An important task in multi-user MIMO-OFDM systems is the design of frequency scheduling algorithms that take into account the spatial and spectral degrees of freedom of the individual user channels. During the reporting period, the subcarrier allocation schemes developed during M1-M12 have been extended and applied to multi-user MIMO relaying scenarios. In particular, subchannel assignment in a two-hop OFDM relay system in which the transmitting nodes (source and relay) have access to channel information and interference-related information has been studied. With L-superadditive relay (performance) functions, a simple ranking of subchannels leads to the optimal assignment with a very low computational complexity.

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 ETHZ, FBM-UPF, FTW, NOK, 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: *Space-time codes for Rayleigh fading MACs (ETHZ).* A significant body of results on space-time and space-frequency coding for single-user channels is available in the literature. In contrast, space-time/frequency coding for MACs seems largely unexplored. Building on the framework in Gallager, IEEE Trans. IT, 1985 for characterizing the dominant error event regions in single-antenna additive white Gaussian noise (AWGN) MACs, we derived rate-dependent space-time/frequency code design criteria for Rayleigh fading multiantenna MACs with perfect channel state information at the receiver during year 1 of MASCOT. It was demonstrated that, depending on the transmission rate tuple, joint designs taking the presence of multiple users explicitly into account may be necessary. Our results furthermore allow to identify the rate regions where, for each user, employing codes designed for the single-user case is optimal. During year 2, these results have been deepened and contributed to deliverable D1.2.1.

Golden codes and concatenated codes (FTW, NOK, UNICAL, and VUT). The Golden code is a full rate, full diversity 2 x 2 linear dispersion space-time block code (STBC) that was con- structed using cyclic division algebras. The underlaying algebraic structure provides the exceptional properties of the Golden code: cubic shaping and non-vanishing minimum determinant.

Building on the results from year 1, concatenations of the Golden code with an outer trellis code have been developed, with an eye on potential application areas like IEEE 802.16e and 802.11n. The proposed bandwidth efficient concatenated scheme uses the Golden code as an inner multidimensional modulation and a trellis code as outer code. Lattice set partitioning is designed in order to increase the minimum determinant. A general framework for code construction and optimization is developed. It is shown that this Golden Space-Time Trellis Coded Modulation scheme can provide excellent performance for high rate applications. Numerical simulations showed that the proposed scheme achieves significant performance gains over uncoded Golden ST coding. The scheme is shown to be robust for both slow and fast block fading channels.

Coded multiple access (ETHZ, FTW, and VUT). Implementation of multiple access in MIMO systems directly via coding without any spreading or orthogonal access was considered by FTW in collaboration with ETHZ and by VUT. Multi-user LDPC codes for low complexity iterative multiuser detection and decoding systems have been designed and a simulation and per-

formance evaluation tool has been implemented and tested in Matlab and C. The LDPC code design is based on EXIT charts for the multiuser detector. Furthermore, interleave division multiple access 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. Recent aspects considered in this context are joint channel estimation and data detection in pilot-assisted IDMA based on a factor graph framework. Here, Gaussian approximations for the messages exchanged in the sum-product algorithm are used extensively to obtain implementations with feasible complexity.

Fast-decodable ST codes (FBM-UPF and UNICAL). During M13-M24 of MASCOT, full-rate, fast-decodable space-time block codes (STBCs) for 2x2 and 4x2 multiple-input multiple-output (MIMO) transmission have been developed. Conditions for reduced-complexity maximum-likelihood decoding have been derived and applied to a unified analysis of two families of 2x2 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 4x2 STBC has been designed that outperforms all previously known codes with certain constellations.

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

Deliverables: Deliverable D1.2.1, entitled "Multi-user space-time code design and database of specific code constructions" was delivered in time by June 30, 2007, thereby also settling milestone M1.2.2, "Database of multi-user space-time/space-frequency codes available" that was scheduled for M18.

Task 1.3

Within this task, contributions came from partners ETHZ, FhG-HHI, FTW, 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. Finally, efficient implementations of the random set theory based detection and estimation algorithms have been considered.

Data detection (ETHZ and VUT). A major thread of the research dealing with MIMO detection was targeted towards soft instead of 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 a similar vein, the efficient MIMO receivers based on partial linear channel equalization followed by mismatched sphere decoding that have been developed during year 1 of MASCOT have been extended to provide soft-outputs. Preliminary numerical results corroborate the conjecture that using this approach in a coded MIMO system provides a continuous trade-off between receive diversity and computational complexity similar to the uncoded hard detection case.

Another approach to reduce MIMO detection complexity was motivated by the fact that the poor performance of low-complexity linear equalization schemes is due to poorly conditioned channel realizations. The simple idea then is to use a low-complexity equalizer for well-conditioned channel realizations and full-diversity detection for less frequently occurring poorly conditioned channel realizations.

Lattice reduction algorithms. 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. A major achievement in the second year of MASCOT was an analytical assessment of the worst-case and average complexity of LLL lattice reduction when applied to fading MIMO channels. 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. Furthermore, based on an efficient implementation, it was demonstrated that the Seysen algorithm requires fewer iterations than the LLL algorithm.

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.

Robust and optimum MIMO transreceivers (FhG-HHI, FTW, and Polito). The problem of optimum pilot-symbol aided receiver structures for fading MIMO channels has 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. Numerical results demonstrated that substantial gains are achieved with the optimum receiver. Furthermore, the approach has been empirically verified via measured real-world MIMO channels.

In a similar spirit, the mismatch caused by channel estimation errors motivated the design of transceiver algorithms that are robust to such errors. As a first step, robust transceiver design for imperfectly known finite impulse response channels was addressed by showing how imprecise knowledge, modeled using uncertainty regions, leads to semidefinite program descriptions of the transceiver algorithms. Thus, efficient algorithms based on convex optimization may be applied in the implementation of the transceivers. Later on, extension of these techniques to the MU-MISO (Multiple Input-Single Output) and MU-MIMO scenarios have been developed.

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. Efficient approximations to vector perturbation involve lattice reduction techniques followed by sub-optimum precoding schemes (e.g., zero-forcing or Tomlinson-Harashima precoding). While lattice reduction is usually achieved via the LLL algorithm, we proposed a computationally significantly less expensive lattice reduction that is based on Brun's algorithm borrowed from algorithmic number theory. It was shown that in spite of its low complexity, the resulting scheme has the potential to exploit a large fraction of the available diversity. The VLSI implementation of this algorithm was performed in close collaboration with Workpackage 2.

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.

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

Deliverables: Deliverable D1.3.1, entitled "Baseband transceiver algorithms preliminary version" and scheduled for M24 was delivered by Dec. 20, 2007.

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: A significant part of the work carried out in this task focused on fixed-point requirements and implementation tradeoffs for matrix-decomposition algorithms such as singular-value decomposition (SVD) and sorted QR decomposition. These operations are essential in almost all types of MU-MIMO transceivers and consume a significant portion of the overall complexity of corresponding VLSI implementations. Hence, optimization for complexity-reduction and obtaining a better understanding of the available complexity/performance trade-offs (design-space exploration) is an essential research topic. Together with corresponding implementations (obtained in Task 2.2) the results of this work have been reported in several publications, including one publication that was awarded a student best-paper award at the 2007 IEEE Asilomar Conference.

Effort has also been put into the performance and complexity analysis of soft sphere decoding. The use of sphere decoding for soft-output MIMO detection and for soft-input soft-output MIMO detection has been evaluated. For this evaluation a complexity analysis of iterative MIMO detection using soft-output sphere decoding has been carried out. The impact of modifications to the soft-output single tree search (STS) sphere decoding algorithm in order to reduce silicon area has been analyzed. Corresponding algorithms and architectures have been reported in several past and upcoming journal and conference publications.

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

Deliverables: By June 30, 2007, the deliverable D2.1.2 named "Selected transceiver algorithms and corresponding complexity-performance trade-offs" has been delivered. The corresponding document focuses on selected transceiver algorithms for multi-user MIMO communication systems which constitute a major implementation challenge. The report describes these key algorithms, introduces suitable optimizations for complexity reduction, proposes suitable low-complexity hardware architectures and discusses the associated implementation trade-offs.

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. This year's focus was put on MIMO preprocessing algorithms including sorted MMSE QR decomposition and singular value decomposition.

Progress: So far, our efforts related to this task were focused on the design and optimization of low-complexity VLSI architectures for MIMO preprocessing algorithms, in order to deliver valuable contributions to the VHDL reference design library.

First, we finalized and published the VLSI implementation of an iterative sorted MMSE QR decomposition (QRD) algorithm suitable for MIMO preprocessing purposes. The design was implemented in four architectural variations on a test chip in 180nm CMOS technology in order to provide different reference circuits for iterative sorted MMSE QRD. All integrated designs proved to operate properly on the ASIC tester, and have been characterized for timing and power consumption.

Second, we presented the efficient VLSI implementation of a singular value decomposition (SVD) algorithm. The test chip in 180nm CMOS technology contains two reference circuits. All integrated designs proved to operate properly on the ASIC tester as well, and have been characterized for timing and power consumption.

Deviations: The work has progressed extremely well, so that more effort can be dedicated to task 2.3 in 2008.

Deliverables: No deliverables in Task 2.2 were due during the reporting period. The developed circuits will contribute to the library of VHDL reference designs.

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. This year's focus was put on the development of a multi-user MIMO system comprising a basic MAC layer and a MIMO-OFDM PHY using the integrated FPGA platform VAMP in conjunction with the newly integrated 4x4 MIMO RF Quad-BAT.

Progress: Most engineering effort in this task was put into the development of the new MU-MIMO testbed with integrated RF boards and on the development of a suitable MAC architecture and a basic MAC protocol.

The design of a basic MAC layer, the implementation of a corresponding architecture and the integration with the PHY layer (M2.3.1) has been completed. The system components have been verified and over-the-air testing is in progress. The MAC layer protocol is written in C code and is running on the PowerPC. The MAC and PHY communicate with each other over the processor local bus (PLB) and the advanced high-speed bus (AHB) interface.

In addition to the real-time testbed, a downscaled testbed with real-time transmission and offline-processing has been implemented and tested over-the-air. In that testbed, precomputed frames are written to the Quad-Bat hardware platform developed within MASCOT, then transmitted over-the-air and the received signal is read back into Matlab for further processing. This testbed is complementary to the real-time testbed and is used for experiments which do not require full real-time signal processing.

To demonstrate MU-MIMO, it was necessary to replicate and extend the ETHZ FPGA prototyping platform and to develop the Quad-Bat RF boards. For the redesign of the ETHZ FPGA prototyping platform, the obsolete parts needed to be replaced. The necessary changes to the schematic and layout were carried out.

Measurements were carried out for the characterization of the PHY layer of the ETHZ MIMO-OFDM testbed using the channel emulator.

Deviations: M2.3.2 is slightly delayed compared to the original time schedule. The main reasons for this delay is an underestimation of the effort required for the implementation of a MU-MIMO demonstration and the redesign of the FPGA prototyping platform (VAMP1b) which was planned to be outsourced to a experienced company but failed due to too high costs (see risk analysis in Deliverable D2.3.1, section 3.2). Nevertheless, we are still confident that we can meet the goals of the MASCOT project.

Deliverables: By April 30, 2007, the deliverable D2.3.1 named "Hardware extension and MAC upgrade for MIMO Testbed" has been delivered. It documents the hardware extensions and the MAC upgrade for the MIMO-MU testbed. It also defines a roadmap for the work ahead. By December 31, 2007, the deliverable D2.3.2 named "Report on MIMO-MAC extension" is due. The MASCOT project steering committee agreed to split the original deliverable D2.3.2 into three parts for the following reasons:

- Delay compared to the original time schedule
- No more reports are required for the remaining work done in work package 2.3.

The time schedule for the entire deliverable D2.3.2 now looks as follows:

- D2.3.2a: Report on MIMO-MAC extensions (M24)
- D2.3.2b: Report on the testing of MIMO-MAC algorithms (M30)
- D2.3.2c: Report on results for second ETHZ open house event (M36)

Milestones: Milestone M2.3.1 (Testbed extension completed) has been reached with slight delays. All components of the MU-MIMO testbed have been verified and over-the-air testing is in progress together with the work on M2.3.2 (MIMO-MAC algorithms tested) which is due by December 31, 2007 but will be delayed until M30 due to the reasons outlined in the deviations section above.

1.3 Workpackage 3

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

Task 3.1 (Partners: PoliTo, FTW, and FhG-HHI)

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 MIMO channel with interference in [55]. In this work they consider the separately-correlated Rician fading MIMO channel with narrow-band interference and calculate its channel capacity with the only limitation that the receive correlation matrix is common for both the intended user signal and interference. A simple method to derive the ergodic capacity and the corresponding capacity-achieving covariance matrix for a MIMO fading channel with multiuser interference is provided. The method applies when the fading distribution is based on the separately-correlated (Kronecker) Rician fading model (with common receive correlation), as the number of antennas grow asymptotically large. PoliTo and FTW compare the results with those obtained numerically in the interference-free case. Then, the analysis is extended to other MIMO channels affected by interference and assess the effect of covariance optimization against i.i.d (independent and

identical distributed) power allocation i.i.d transmitted symbols. Numerical results are provided to assess the accuracy of the asymptotic analytic method.

Then PoliTo and FTW studied the second-order statistics of the mutual information of the separately correlated Rician fading MIMO channel with interference in [46]. In this work, PoliTo and FTW are interested in finding an analytic expression of the moment generating function of the asymptotic mutual information. Our findings are based on the replica method, which allows to derive the moment generating function of the mutual information. Basically, the approach used by Moustakas is extended to the correlated Rician fading case and derive the mean and the variance of the mutual information. Then they solved the problem when there exists line-of-sight by applying the methods of super-analysis developed in the context of theoretical physics. The mean and variance of the mutual information of a separately-correlated Rician fading MIMO channel are derived in the presence of multi-access interference, when the number of transmit and receive antennas grows asymptotically large. Perfect receive channel-state information is assumed. Analytic asymptotic results are compared with Monte-Carlo simulations to assess the accuracy of this method when the number of antennas is small.

Next PoliTo and FTW studied the performance limit of the multiuser case in [47]. They investigated the ergodic capacity region of a multiple access separately-correlated Rician fading MIMO channel using an asymptotic approach. It is assumed that the number of transmit and receive antennas grow asymptotically approaching finite values while the number of users and the SNR are kept finite. In this work, it was assumed that the receiver has full CSIR and the transmitter knows the statistics of the channel, i.e. the transmitter has channel distribution information (CDIT). Based on these assumptions, PoliTo and FTW provide an algorithm to find the maximum ergodic sum-rate achieving covariance matrices of a multiple-access MIMO channel when the number of transmit and receive antennas grow asymptotically large with finite asymptotic ratios and the number of users and their SNR's are finite. In this context, it is assumed that the multiple-access communication channel is affected by Rician fading with separate spatial correlation (with a common receive part and different transmit parts). Our results rely on a previous work [55] where the ergodic capacity achieving covariance matrix was obtained for a separately-correlated Rician fading MIMO channel with multiple-access interference, which extended previous results due to Moustakas relevant to the case of Rayleigh fading. It is shown by numerical results that this asymptotic approach is very accurate even when the number of antennas is as low as a few units. The ergodic capacity achieving covariance matrices for all users are derived according to the algorithm provided and the corresponding capacity is compared with the mutual information achieved by

i.i.d. power allocation. Monte-Carlo simulations are also reported in order to verify the accuracy of the asymptotic results.

Further, FhG-HHI contributed to deliverable D3.1.1 with novel results on the characterization of capacity regions by means of interference functions. The analysis of capacity regions is complicated by interference between the communication links. This typically results in a coupled system with many degrees of freedom. So the general characterization of wireless capacity regions is complicated, especially when additional system constraints are considered. This motivates an abstract approach, which focuses on some core properties. One outcome of the project was to show 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.

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

Deliverables: Contributed to D3.1.1: Performance tradeoffs in MU-MIMO systems, Editors: Jialai Weng, Giorgio Taricco, June 30, 2007. Contributed to D3.1.2: Capacity regions of MU-MIMO systems, Editors: Jialai Weng, Giorgio Taricco, December 31, 2007.

Task 3.1 (Partners: ETHZ)

Objectives: Task 3.1 is concerned with achievable information rates and performance tradeoffs. Before tackling the multiuser case, the fundamental tradeoffs of the point-to-point MIMO channel need to be investigated.

Progress: The diversity-multiplexing tradeoff allows to efficiently characterize the information-theoretic performance limits of communication in MIMO fading channels both in the point-to-point and in the multiple-access case. Our work in this task has established the diversity-multiplexing tradeoff curve of selective-fading (i.e. selective in time, frequency or time-frequency) point-to-point channels, and we have presented a code design criterion that guarantees optimal performance. These results have been published in [21].

In addition, we showed that the DM tradeoff optimal code design criterion corresponds (for fixed rates) to the classical rank criteria reported in literature for time, frequency and time-frequency selective channels and, moreover, that it is tightly connected to the criterion for approximate universality in flat-fading. We also have studied the systematic design of optimal codes in selective-fading channels. In particular, optimal codes can be constructed

by splitting the design problem into two simpler and independent problems: the design of an inner code, or precoder, adapted to the channel statistics (i.e. selectivity characteristics) and an outer code independent of the channel statistics.

We started using the DM tradeoff framework to study the selective-fading multiple-access MIMO channel. On the conceptual level, our approach consists in relating the notion of dominant error event regions — introduced by Gallager — to the DM tradeoff framework.

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

Deliverables: Contributed to D3.1.1: Performance tradeoffs in MU-MIMO systems, Editors: Jialai Weng, Giorgio Taricco, June 30, 2007.

Task 3.2 (Partner: NOKIA)

Objectives: Task 3.2 is concerned with the performance of mobile ad-hoc wireless networks (MANETs) and relays with with collaborative use of multiple antennas.

Progress: During 2007, this activity focused on the use of channel state information in (distributed) relay networks:

- Study of centralized and decentralized subchannel allocation concepts using optimization theory (mostly game theory and linear programming). In the considered systems the transmitting nodes (source and relay) have access to channel information and to some interference-related information. Distributed resource allocation (subcarrier or beam assignment) is modeled as a noncooperative game where the players are the source nodes. QoS-aware source nodes opportunistically select their transmission resources while a multi-antenna or multi-channel channel-aware relay node assigns the resources at the relay in a way that maximizes the sum of utilities at the destination nodes. The beam allocation game is modeled as a potential game for which the implicit joint objective (potential) of the source nodes

- Development of algorithms for a relay selection problem (i.e. which relays are to be used by which source nodes?). This work will continue in 2008.

- Performance analysis of a MIMO relaying schemes with multi-antenna relay nodes and multi-antenna source and destination nodes. In particular, we considered a randomized multiuser MIMO relay network with M sources. Each source and the destination node have multiple transmit/receive antennas. The R relay nodes have only one antenna transmit and receive antenna, and they pseudo-randomly vary the transmission signal, and generate a time-varying MIMO channel to the destination node. The destination schedules the transmissions of delay-differentiated services of the M sources. Both opportunistic and centralized scheduling policies were considered and it was seen that with both schedulers the resulting capacity is similar, and that delay differentiation is effective. Increasing the number of transmit and receive antennas reduces the scheduling gain considerably.

- Study of algorithms and feedback strategies for scalable relay networks (where CSI feedback rate from destination to relays scales "sublinearly" with the number of relay nodes). Initial results available, and work continues in 2008.

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

Deliverables: No deliverables were due during the reporting period.

Task 3.2 (Partner: FBM-UPF)

Objectives: Task 3.2 is concerned with the performance of mobile ad-hoc wireless networks (MANETs) equipped with multiple antenna arrays.

Progress: A new algorithm for the detection of neighbors in a wireless network has been developed and analyzed. This is based on multiuser detection concepts, which prevent the algorithm from collapsing when collisions among users are present. A large-system analysis has been initiated, to examine the performance of random-set-based multiuser detection techniques in the presence of a large number of users.

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

Deliverables: No deliverables were due during the reporting period.

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 is continuously updated. Here, the project announces events, tutorials, special sessions, publications, deliverables, and achievements. During 2007, the web-site also served as on-line registration desk for the tutorial (Delverable D4.3) and the industry course (Deliverable D4.4). It is accessible through the following URL:

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

1.4.2 Publications 2007

Details on the publication plans and policy can be found in MASCOT Deliverable D4.2. MASCOT's list of publications 2007 can be found at the end of this Periodic Activity Report 2007.

Journals

MASCOT contributions have been submitted to a number of important international journals during 2007:

- IEEE Journal on Selected Areas in Communications,
- IEEE Transactions on Information Theory,
- IEEE Communications Letters,
- European Transactions on Telecommunications.

1.4.3 WSA 2007 with full-week tutorial

FTW and VUT organised the ITG/IEEE Workshop on Smart Antennas (WSA 2007) in Vienna, Austria on February 26–27, 2007. The WSA 2007 homepage is hosted on the MASCOT web-site:
`http://www.ist-mascot.org/wsa2007/` .

MASCOT Deliverable D4.3 is the *Full-week tutorial on MU-MIMO*. The tutorial was held from February 28 to March 2, 2007 at the premises of FTW. The tutorial was organised jointly with the FP6-IST project SURFACE. The

liaison between MASCOT and SURFACE enabled a co-ordinated planning of the tutorial's contents.

The full MU-MIMO Tutorial programme is available at the following link: http://www.ist-mascot.org/Members/cfm/tutorial-on-multiuser-mimo/.

The tutorial was attended by 52 participants.

The following topics were discussed:

1. MIMO basics, multiplexing-diversity tradeoff, capacity of wireless channels: ergodic capacity, outage capacity
2. Multiuser capacity and opportunistic communication
3. MIMO multiuser basics, multiple-access schemes, and multiuser space-time coding
4. Multi-User MIMO Sum-Rate Capacity Optimization Based on Iterative Water- Filling
5. Channel-aware multi-antenna multi-user relay networks

Information lossless space-time coding for multiple access systems

Algebraic tools for code design in MIMO systems

6. Resource allocation, interference functions, specialised to OFDMA broadcast channels
7. Using random-set theory for multiuser detection and neighbor discovery on wireless networks
8. MIMO multiuser OFDMA link and system performance
9. Minimum BER Linear MIMO Transceiver Design
10. VLSI Implementation of MIMO systems
11. MU-MIMO scheme performance evaluations using measured channels in specific environments
12. Multi-antenna broadcast precoding

List of Contributors from MASCOT partners

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Boche, H.	FhG-HHI
Bölcskei, H.	ETHZ
Burg, A.P.	ETHZ
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Matz, G.,	VUT
Mecklenbräuker, C.F.	FTW
Schubert, M.	FhG-HHI
Seethaler, D.	VUT
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Weng, J.	PoliTo
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List of Contributors from SURFACE partners

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Pages Zamora, A.	Universitat Politecnica de Catalunya, Barcelona, Spain

1.4.4 Industry Course

The industry course (Deliverable D4.4) was held in the auditorium of the Nokia Research Center in Helsinki, Finland on Friday, November 16, 2007. The industry course was attended by 30 participants. Further details can be found at the following link:
http://www.ist-mascot.org/industrycourse

List of Contributors

Bölcskei, H.	ETHZ	MASCOT
Hottinen, A.	NOK	MASCOT
Mecklenbräuker, C.F.	FTW	MASCOT
Schubert, M.	FhG-HHI	MASCOT
Viterbo, E.	UNICAL	MASCOT

1.4.5 First ETHZ Open House Event

The first ETHZ Open House Event (Deliverable D4.5) is planned for Friday, February 22, 2008. Further details on the programme and registration can be found at the following link:
http://www.ist-mascot.org/deliverables/deliverable-4.5

1.4.6 Special sessions 2007

The liaison between MASCOT and FP6-IST project SURFACE enabled a concerted planning of special sessions at conferences. The following special sessions were organised to publish results from the MASCOT and SURFACE projects and held in 2007:

SPAWC 2007. Special session on "Optimization of Multiple-Channel Systems", chair: Ari Hottinen (Nokia Research Center), in June 2007. This special session disseminated recent results related to transceiver optimization and resource allocation in multi-channel links and networks. The papers in the session address both theoretical and practical aspects in multi-channel (MIMO,OFDMA, relay, etc) networks, ranging from optimal channel assignment at transmitter(s) to optimal receiver design.

EUSIPCO 2007. A special session on "Optimization of Wireless Multiuser MIMO Communication Systems", chair: Christoph Mecklenbräuker (FTW), Poznan, Poland, in September 2007. The goal of this special session was to highlight optimization techniques for multi-user MIMO communications both in cellular networks and in ad-hoc mode. This session will highlight recent advances in multi-user MIMO techniques on the physical-, medium access-, and radio link control layers. Currently, little is published about how to optimally leverage the new degrees of freedom resulting from MIMO terminals in a multi-user context. The wireless industry has started to integrate single-user MIMO techniques into existing multi-user cellular standards and to define new cellular standards based on MIMO. Wireless networks should not be regarded as a set of concurrent point-to-point links. More appropriate models are many-to-one links where many users transmit to a single base station and one-to-many links where a single base station transmits to many users.

Planning of special sessions 2008

- We have planned a special session on *Complexity Reduction in Multiuser MIMO Systems* during EUSIPCO 2008, Lausanne, Switzerland.

1.4.7 Dissemination in the Far East

During December 2007, Prof. Ezio Biglieri was invited to a series of talks about MASCOT research at National Taiwan University (Taipei, ROC), National Dong Hwa University (Hualien, ROC), and National Sun Yat-Sen University (Kaohsiun, ROC). Prof. Biglieri's presentation can be found here
http://www.ist-mascot.org/workpackages/wp4

1.4.8 Standards

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 first results will be published at the ITG/IEEE Workshop on Smart Antennas (WSA 2007).

1.4.9 Exploitation activities

Intellectual Property Right management

The project partners established an IPR Policy Committee consisting of technical experts and legal experts in September, 2006[1]. 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[2] 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[3].

[1] see Technical Annex (Description of Work): [43], Section 6.2.2, page 19.

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

[3] The 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—6 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 industry[4]. 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.

[4]see Technical Annex [43], 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 http://www.ai.tuwien.ac.at
6	ETHZ	ETH Transfer http://www.vpf.ethz.ch/transfer/index_EN
7	FBM-UPF	Business innovation & development responsible: Ms. Marta Ysern
8	UNICAL	to be defined

Table 1.1: Technology transfer institutions which will aid in exploitation, especially concerning the licensing of the VHDL reference designs.

Chapter 2

Consortium Management

2.1 Project Steering Committee

The current members of the project steering committee (PSC) are [43, 44]:

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 [44] and below).

During 2007, the PSC convened four times:

- 5th PSC meeting, Vienna, February 28, 2007.
- 6th PSC meeting, Barcelona, May 21, 2007.
- 7thPSC meeting, Phone Conference, September 14, 2007.
- 8th PSC meeting, Cosenza, December 4, 2007.
- 9th PSC meeting, Zürich, February 22, 2008.

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.

2.2 MASCOT workshop at UNICAL

During December 3–4, 2007, an internal workshop was organised at UNICAL to further deepen the collaboration among partners and workpackages. This workshop was attended by 20 researchers from MASCOT partners. The first day was solely devoted to scientific talks by researchers from the MASCOT partners to inspire informal discussions for future collaboration within the project during 2008. The second day was devoted to strategic decision making and project management. The scientific scope and roadmap was defined for the submission of a new project proposal to the FET Open Call in FP7. The detailed workshop programme can be found at the following URL

http://www.ist-mascot.org/Members/cfm/mascot-workshop-unical

2.3 Liaison between MASCOT and SURFACE

During June 2006, a liaison between the two FP6–IST projects SURFACE and MASCOT was established. Both projects participate in the Broadband Air Interfaces (BAI) cluster which is moderated by Sylvie Mayrargue (CEA–LETI) [37]. 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, MASCOT implements VHDL reference designs and validates them on a hardware testbed.

Further, the liaison aims at a close cooperation on dissemination and exploitation. It is planned to organise joint workshops and tutorials with participation from both projects.

- The multi-user MIMO tutorial in connection with WSA 2007 is jointly organised by MASCOT and SURFACE.

- Joint special sessions were organised for SPAWC 2007, Helsinki, Finland, and EUSIPCO 2007, Poznan, Poland, with mixed contributions from MASCOT and SURFACE (session organisers: A. Hottinen and C.F. Mecklenbräuker).

2.4 Short Visits

- 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 of 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 of 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.

Publications 2007

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