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MASCOT

Multiple-Access Space-Time Coding Testbed

Specific Targeted Research Project

IST

Publishable Final Activity Report

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Contents

Chapter 1

Project Execution

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

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

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

WP3: Performance limits and tradeoffs. Understanding of the performance limitations and tradeoffs in MU-MIMO systems is still patchy. We therefore plan to investigate information-theoretic performance limits of MU-MIMO systems under realistic propagation conditions. We will also study the tradeoffs between different MIMO gains in the multi-user context. This will provide us with insights into problems related to system design.

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

WP1 focused on MU-MIMO resource allocation and proportionally fair schedulers, MU-MIMO space-time codes for multiple access, and MIMO transceiver schemes emphasising receivers with incomplete information about numbers 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 D1.3.2, some of which have been made available as a VHDL reference design in WP2.

WP2 focused on the the design-space exploration for channel matrix preprocessing algorithms, the VHDL reference designs, and the MU-MIMO OFDM testbed. Key results from WP2 are the VHDL Library of Reference Designs which have been made available as deliverable D2.2.1 and several architectures and ASIC implementations of channel preprocessing algorithms.

The research in WP3 focused mainly on the characterisation of multiuser capacity, quality-of-service regions, and ARQ 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. A key result from WP3 is the characterisation of the ergodic capacity of the asymptotic separatelycorrelated Rician fading MIMO channel with interference.

In total, more than 180 contributions to journals and conferences were published from MASCOT and eight patent applications produced.

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

1.1 Project objectives and major achievements

1.1.1 Deliverables

All deliverables of the project can be accessed online via the following link

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

Deliverables with key results are:

- Deliverable D1.3.2: *Baseband transceiver algorithms — final version incorporating feedback from WP2 and WP3*
- Deliverable D2.2.1: *VHDL Reference Designs*
- Deliverable D3.1.3: *Report on capacity regions of MU-MIMO systems (final report)*
- Deliverable D3.2.2: *Signalling/routing strategies and outage properties in Ad-hoc MIMO networks*

1.1.2 Patents

The IPRs generated by the project are evaluated by the IPR Policy Committee for patent filing or for exploitation. In total, there were eight patent applications (all applications by Nokia).

1.2 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.

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.

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.

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.

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.

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.

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].

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.

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.

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.

[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.

At the receiver side, multiple antennas are *always* beneficial since an array 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.

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 eld strength jointly with the number of available dimensions in the signal space for specic 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 nds the best antenna array conguration 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 efcient use of the infrastructure results in fewer base stations for the same performance, compared to a manual design.

1.3 SWOT Analysis of Sphere Decoding

1.3.1 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.

1.3.2 SWOT Analysis

A summary of the SWOT analysis for sphere decoding in multi-user MIMO communications is provided in Fig. 1.1. 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:

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.

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 1.1: SWOT analysis for sphere decoding

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 2

Dissemination and Use

2.1 Web-site

The public web-site [60] 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

2.2 Press

The start of the MASCOT project was announced by FTW and VUT in press releases (January 2006).

As part of the dissemination activities, the ETHZ Open House Event was announced by ETHZ in the *Neue Züricher Zeitung* (NZZ) (February 2008).

2.3 Testbed Demonstration on Video

As part of the dissemination activities, ETHZ produced a video about the MU-MIMO testbed for the ETHZ Open House Event which is distributed online as a podcast:
http://www.podcast.ethz.ch/episodes/?id=734

2.4 Publications

2.4.1 Journals

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

- 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).
- IEEE Transactions on Signal Processing (TSP),
- EURASIP Journal on Advances in Signal Processing (JASP),

2.4.2 WSA 2007 with MU-MIMO 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 from the following affiliations:

European Office of Aerospace Research & Development	United Kingdom
National Physical Laboratory	United Kingdom
University of Rome	Italy
Universitat Pompeu Fabra	Spain
University of A Coruna	Spain
Universitat Politecnica de Catalunya	Spain
Fraunhofer Gesellschaft	Germany
ETH Zürich	Switzerland
Chungbuk National University	South Korea
Ericsson Research	Germany
T-System Enterprises Services	Germany
Aalburg University	Denmark
TU Darmstadt	Germany
Vienna University of Technology	Austria
ARC, Division Smart Systems	Austria
FTW	Austria
NTT Network Innovation Labratories	Japan
Nokia	Finland
TU München	Germany
TU Ilmenau	Germany
Universität Duisburg-Essen	Germany
mimoOn GmbH	Germany
University of Bremen	Germany
TU Delft	Netherlands
Politecnico di Torino	Italy
Universita della Calabria	Italy

The following topics were discussed:

- MIMO basics, multiplexing-diversity tradeoff, capacity of wireless channels: ergodic capacity, outage capacity
- MIMO multiuser basics, multiple-access schemes, and multi-user space-time coding
- Multiuser capacity and opportunistic communication
- Multi-User MIMO Sum-Rate Capacity Optimization Based on Iterative Water-Filling
- 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
- Resource allocation, interference functions, specialised to OFDMA broadcast channels
- Using random-set theory for multiuser detection and neighbor discovery on wireless networks
- MIMO multiuser OFDMA link and system performance
- Minimum BER Linear MIMO Transceiver Design
- VLSI Implementation of MIMO systems
- MU-MIMO scheme performance evaluations using measured channels in specific environments
- Multi-antenna broadcast precoding

List of Contributors from MASCOT partners

Biglieri, E.	FBM-UPF,
Boche, H.	FhG-HHI
Bölcskei, H.	ETHZ
Burg, A.P.	ETHZ
Hottinen, A.	Nokia
Lechner, G.	FTW
Matz, G.,	VUT
Mecklenbräuker, C.F.	FTW
Schubert, M.	FhG-HHI
Seethaler, D.	VUT
Taricco, G.	PoliTo
Viterbo, E.	UNICAL
Weng, J.	PoliTo
Zemen, T.	FTW

List of Contributors from SURFACE partners

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Fonollosa, J.	Universitat Politecnica de Catalunya, Barcelona, Spain
Garcia, L.	Universitat Politecnica de Catalunya, Barcelona, Spain
Pages Zamora, A.	Universitat Politecnica de Catalunya, Barcelona, Spain

2.4.3 Special sessions

The liaison between MASCOT and FP6-IST project SURFACE enabled a concerted planning of special sessions at conferences. The following special sessions related to MASCOT and SURFACE topics were organised:

EUSIPCO 2006. A two part special session on multiuser MIMO communications, (Parts I and II), chair: Christoph Mecklenbräuker, Firenze, Italy.

Asilomar 2006. Special session on MIMO equalisation, chair: Christoph Mecklenbräuker, Pacific Grove (CA), USA.

SPAWC 2007. Special session on "Optimization of Multiple-Channel Systems", chair: Ari Hottinen (Nokia Research Center), in June 2007.

EUSIPCO 2007. A special session on "Optimization of Wireless Multiuser MIMO Communication Systems", chair: Christoph Mecklenbräuker (FTW), Poznan, Poland, in September 2007.

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.

2.4.4 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)

For further details please see the following links:
http://www.ruf.rice.edu/~mobile/WINTECH2008/demo_contest.htm
http://www.sigmobile.org/mobicom/2008/index.html

2.5 Industry Courses

2.5.1 First Industry Course on MU-MIMO

The first industry course (Deliverable D4.4) was held in the auditorium of the Nokia Research Center in Helsinki, Finland on Friday, November 16, 2007, see Figure 2.2. The industry course was attended by 30 participants.

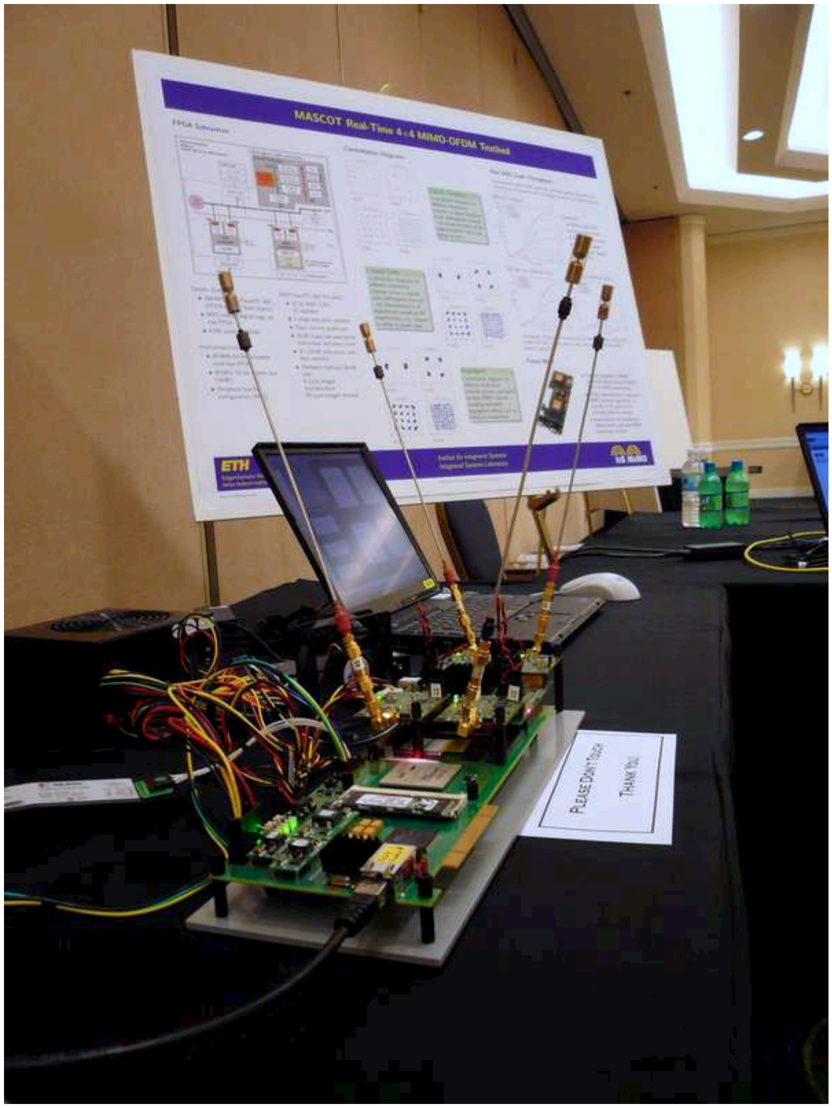

Figure 2.1: Multi-User MIMO Testbed at WinTech'08 Demo Contest, San Francisco, Sep. 19, 2008

Figure 2.2: Participants of the MU-MIMO Industry Course, held on November 16, 2007 at the Nokia Research Center, Helsinki.

List of Contributors

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

2.5.2 Second Industry Course on MU-MIMO

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

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

The following topics are discussed:

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

List of Contributors

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

2.6 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

2.7 Standards

2.7.1 WiMax

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

2.7.2 Digital Video Broadcast

E. Viterbo (UNICAL and Nokia) prepared the DVB contribution *Algebraic Rotations for Fast Fading Channels* while being a Visiting Fellow at Nokia Research Center. In this proposal to the standardisation of DVB, the basic ideas underlying algebraic code design for fast fading channels are reviewed as a proposed enhancement to DVB-T2. It is concluded that rotated multidimensional constellations combined with component interleaving can provide large diversity gains at the expense of higher decoding complexity only. There is no penalty in bandwidth. Considering small dimensions 2 to 4, the increased complexity is totally feasible for hardware implementations.

2.7.3 Universal Mobile Telecommunications System

In 2007, the 3GPP agreed to standardize D-TxAA (Dual Stream Transmit Antenna Array) as the MIMO extension for HSDPA (High Speed Downlink Packet Access). In their work, C. Mehlführer, S. Caban, and M. Rupp (all affiliated with VUT) investigate the performance of two low-complexity receivers for D-TxAA by performing outdoor-to-indoor measurements in the inner city of Vienna. This work is submitted to EUSIPCO 2008 for publication in a planned special session (see also Section **??**).

2.8 Exploitation activities

2.8.1 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].

2.8.2 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[4] and academic institutions.

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[1] see Technical Annex (Description of Work): [121], 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

[4] 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 2.1: Technology transfer institutions which will aid in exploitation, especially concerning the licensing of the VHDL reference designs.

The legal support of ETH Transfer, the technology transfer department of ETH Zurich, will then be solicited in questions relating to invention protection and exploitation, as well as preparation and negotiation of relevant contracts with potential industrial partners. Similar services will be provided by corresponding units at FhG-HHI, PoliTo, and VUT (see Table 2.1) on a per partner basis.

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

2.8.3 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.

2.8.4 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.

2.9 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

2.10 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) [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, 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).

- SURFACE partners were invited to the First MU-MIMO Industry Course, Helsinki, November 11, 2007.

Chapter 3

Publishable results

- The MASCOT deliverables are publicly available on the web-site at the following URL http://www.ist-mascot.org/deliverables
- In Section "Publications", all scientific publications resulting from MASCOT research during 2006—2009 are listed.

Chapter 4

Other Issues

There are no other issues to report for MASCOT.

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