European Commission - 6th Framework Programme	**ACE (Antenna Centre of Excellence)**	Information Society Technologies

ACE Deliverable 2.2-D7

Reconfigurable MIMO Transceivers

Project Number: FP6-IST 508009

Project Title: Antenna Centre of Excellence

Document Type: Deliverable

Document Number: *FP6-IST 508009/2.2D7*

Contractual date of delivery: *31st December 2005*

Actual date of delivery: *31st December 2005*

Workpackage: *WP2.2-3*

Security : *Public*

Nature: *Report*

Editor(s): *Monica Navarro (CTTC)*

Author (s): *Monica Navarro (CTTC), Xavier Mestre (CTTC), Miquel Payaró (CTTC), Chriatian Ibars (CTTC), Athanasios Kanatas (UPRC), K. Kyritsis (UPRC), George Bravos (UPRC), G. Efthymoglou (UPRC), Per Zetterberg (KTH), Athanasios Marousis (NTUA), Nikos Skentos (NTUA), Panagiotis Karamalis (NTUA), Atilio Gameiro (IT), Paulo Marques (IT), Adão Silva (IT), Laura García García (UPM), Carlos Gómez (UPM), Ramón Rodríguez-Osorio (UPM), Leandro de Haro Ariet (UPM), Angeliki Alexiou (Lucent), Jean-Claude Belfiore (GET).*

Participant(s): *CTTC, KTH, ICCS/NTUA, IT, Lucent, UPM, GET*

Abstract: The present document presents a review of the-state-of-the-art on advance MIMO transceivers for mobile wireless communications as well as describes the joint research activities carried out during the first phase of the project on advance receiver structures, re-configurable/adaptive transmission schemes and optimised MIMO transceivers.

Keyword list: re-configurable transceivers, adaptive schemes, channel estimation, iterative structures, interference cancellation, partial CSI, beamforming, capacity, MIMO, test-beds.

Table of Contents

Executive Summary

Advanced MIMO transceivers are a key enabling technology in order to address the requirements of future communication systems in terms of higher data rates, enhanced capacity and improved Quality of Service and re-configurability to changing propagation, traffic and service conditions in a multi-technology environment. The objective of this workpackage has been to study the existing approaches, investigate their relative merits in different scenarios, propose modified versions of existing and devise new techniques. This deliverable aims at reporting the work carried out during the first phase of the project in WP2.2-3 and present the new contributions towards spreading the excellence on the field of advanced multiple antenna transceivers .

The objective of the first part of the project has been to review the state-of-the-art on MIMO transceivers, and to identify the knowledge gaps. This preliminary work has provided the grounds for developing the action plan for interaction between partners and foster collaboration among participating researchers from the organizations involved in this workpackage and to some extend workpackage 2.2-4, which activities have been carried out in close collaboration with WP2.2-3.

The progress towards the objectives are briefly introduced here and further developed in following sections of the deliverable.

The research activities described in the deliverable have been structured around four areas, each one associated to one task:

- **Task 2 - Advanced receiver structures**. This task focus on the analysis and design of advanced receivers for channel estimation and interference mitigation under the framework of multiple antenna systems, including the investigation of iterative approaches, development and analysis of blind/semi-blind techniques and design of algorithms that teach the receiver how to optimise resources depending on the channel conditions and training sequence length.
- **Task 3 - Re-configurable/Adaptive Transmission Schemes** are addressed under this task considering the use of multiple antennas for spatial multiplexing purposes, beamforming gains or exploiting diversity features with the objective of developing scalable approaches, so that an optimum transmission strategy is selected according to the available channel state information.
- **Task 4 - Jointly Optimised Transceivers**. The scope of this task is on feedback based transmission schemes.
- **Task 5 - Antenna Technologies for Re-configurable Multiple Antenna Terminals** investigates the requirements and specifications for antenna array design re-configurable to different operating frequencies, radiation patterns and polarisation that provide different diversity gains and interference mitigation capabilities.

The activities and progress related to task 5 on antenna technology are reported in a different deliverable[64].

The integration activities carried out in the framework of the research topics have involved:

- **Review of the state-of-the art** on advanced and re-configurable MIMO transceivers, and to identify the knowledge gaps where the Network should concentrate its efforts to complete and expand the excellence in the field. The outcome of this activity is reported in Section 1.
- **Identification of scientific and development know-how**. Complementary to the state-of-the art review, an extensive report on the know-how of each partner has been carried out from two different points of view: one comprising the scientific expertise and the second related to prototypes and test-beds implementation and development expertise, which outcome is detailed in Section 2. This section also includes the advances and improvements achieved during the first phase of the project on test-bed development and prototype implementation.

- **Identification of knowledge gaps and elaboration of an action plan for collaboration**. Based on the review of the state of the art and the established know-how, identification of knowledge gaps and research interests of the partners were reported and an action plan for future research collaboration and integration was elaborated (Section 2).
- **Internal workshops involving technical discussions and presentations**. Several workpackage meetings have served as a meeting point for in person technical discussions from which collaborations and visits to other partners premises have materialized.
- **Common tools and measurement campaigns**. Common software tools have been developed and measurements campaigns have been performed during phase I of the project.

Besides the workpackage meetings, several phone conferences and informal meetings at international conferences have served to coordinated and realized the workpackage activities, which has involved a large number of participants from the organizations integrated in the workpackage that have been actively engaged in the working process towards achieving the network goals.

The joint research activities have also lead to education, training and dissemination activities, described in detail in Section 7 and summarized here:

- MIMO Communication Systems and Antennas Short Course part of the European School of Antennas
- Antennas for User Terminals: Small Antennas Short Course part of the European School of Antennas
- Master Thesis on design, implementation on a software-radio platform and measurements of a MIMO test-bed for wireless communications at UPM.
- Presentation of ACE activities in the framework of a joint PhD program between University of Aveiro and University of Porto
- Organization of ACE workshop at the IST Mobile and Wireless Communications Summit 2005 on Smart Antennas and Multiuser Communications
- Plenary Lecture at the PIMRC 20005 on Smart Antennas by a member of the Scientific Council.
- Dissemination at the IST concertation and clustering activities
- Publication in several journals, including joint publications,
    - European Transactions on Communications
    - IEEE Transactions on Signal Processing
    - IEEE Communications Magazine
    - IEEE Transactions on Wireless Communications

and international conferences, such as

- IST Summit on Mobile and Wireless Communications
- IEEE Vehicular Technology Conference
- IEEE Sensor Array and Multichannel Signal Processing Workshop
- IEEE (GLOBECOM)
- IEEE International Conference on Acoustics, Speech and Signal Processing
- IEEE Information Theory Workshop
- IEEE International Symposium on Personal Indoor and Mobile Radio Communications

- Asilomar Conference on Signals, Systems and Computers
- COST 273/284 Workshop
- WWRF meetings
- International Union of Radio Science General Assembly and National Symposiums
- IFIP International Conference on Mobile and Wireless Communications Networks

The rest of the deliverable is organized as follows. Section 1 starts reviewing the state of the art structured in the three main identified themes of research. In Section 2 it follows the report on each partner initial know-how and the identified knowledge gaps. Next, each of the tasks are individually described through the joint research activities that have taken place during the project two year period. The listed activities serve as the basis to introduce the technical new contributions to the scientific know-how achieved during this period. Thus, Section 3 refers to task 2 on advanced receivers, Section 4 relates to task 3 on re-configurable, adaptive transmission schemes and Section 5 reports the activities carried out with respect task 4 on jointly optimised MIMO transceivers. Next sections include several activities that are extensive to more than one research subject and that in fact have aided to the development of new scientific contributions in several tasks. In particular, Section 6 describes common tools and available measurement data that have been developed or obtained within the framework of the workpackage research activities. Section 7 reports the education, training and dissemination activities associated to the joint research activities performed within the framework of workpackage WP2.2-3.

1. State of the art on MIMO Transceivers

The objective of this section is to review the state-of-the-art on advanced and re-configurable MIMO transceivers, and to identify the knowledge gaps where the Network should concentrate its efforts to complete and expand the excellence in the field. The identification of such gaps shall provide the motivation and grounds for the work developed under each task of the workpackage.

1.1 Introduction to advanced MIMO transceivers

The demand for capacity in wireless communications (cellular, WLAN's) has grown dramatically in the last decade and as the users will expect the same services with the same quality they enjoy in the fixed network with wireless communications, it is expected to still grow. This provides the impetus for the development of a broadband component in future cellular networks as well as the development of very high capacity WLAN's. In either case, the achievement of the very high bit rates that are envisioned, requires the development of signal processing techniques that take the most from the channel capacity.

One of the key factors that will enable the data rate to increase is the use of multiple antennas at the transmitters and receivers in the system. It has been predicted by the pioneering work on the capacity of MIMO channels [94][95][96][108], that adding the spatial dimension through the use of multiple transmit and receive antennas may bring significant capacity gains, especially when the channel exhibits rich scattering and its variations can be adequately tracked. The large capacity enhancements associated with MIMO channels are based on the premise that a rich scattering environment provides independent transmission paths from each transmit antenna to each receive antenna. Therefore for single user systems, a transmission and reception strategy that exploits this structure achieves capacity on approximately $\min(M,N)$ separate channels where M is the number of transmit antennas and N the number of receive antennas. Thus the capacity scales linearly with $\min(M,N)$ relatively to a SISO system.

The techniques that rely on MIMO structures can be broadly classified into three main categories, spatial multiplexing, diversity and beamforming or space-time equalization techniques.

The *spatial multiplexing* approach exploit the scattering properties of wireless MIMO channels by transmitting several data streams in parallel. We have N combinations of the M transmitted signals. If the channel is well-behaved, so that the N received signals represent linearly independent combinations, we can recover the transmitted signals and thus the data rate can be increased without requiring more spectrum. Practical schemes, like layered space-time (ST) receiver structures [94][97][98] combined with space-time codes [99] allow to approach the capacity limits.

In contrast to spatial multiplexing, pure *diversity* schemes, aim at combating the fading characteristics of the wireless channels rather than exploiting them. By sending signals that carry the same information through different paths, multiple independently faded replicas of the data symbol can be obtained at the receiver. It is well known that if the fading is independent across antenna pairs, a maximum diversity gain (advantage) of N can be achieved: the average error probability can be made to decay like $1/\mathrm{SNR}^N$ at high SNR, in contrast to the 1/SNR for the single antenna fading channel. Antenna diversity at the receiver is well-known, and has been studied for a long time. More recent work has concentrated on using multiple transmit antennas to obtain diversity gains (some examples are trellis-based space-time codes [99][100] and orthogonal designs[101]). However, the underlying idea is still averaging over multiple path gains (fading coefficients) to increase the reliability. In a system with M transmit and N receive antennas, assuming the path gains between individual antenna pairs are i.i.d. Rayleigh faded, the maximum diversity gain is MN, which is the total number of fading gains that one can average over.

The *spatial equalization* concept, has similarities with the approach of spatial multiplexing, but differs in the sense that the goal is kept at a more limited level. The channel structure and scattering properties are not exploit to define independent channels, through where different data streams are transmitted, but the objective is such that at the receiver output or at some point in the link one gets waveforms suitable for decision, i.e. the main objective is to exploit the properties of a MIMO channel in order to get an equivalent SISO channel with good properties. Spatial equalization can be applied at the reception, at the transmission or at both ends of the communication link. Spatial equalization requires the knowledge of the channel characteristics. Depending on the considered approach, this can be instantaneous knowledge of the complete channel response, long term statistics or partial knowledge (e.g. DOA). While the conventional equalization scheme, beamforming, basically consists in focusing the energy into some desired directions [102][103][104] (and eventually nulling for others) leading to an increase of the average SNR, other approaches exploiting other characteristics of the channel have been proposed in recent years for various systems (e.g. [105][106][107]).

Future wireless systems are expected to offer optimized performance by achieving adaptedness to varying propagation and network conditions. For the design of reconfigurable transceivers, the Channel State Information (CSI) available at the transmitter and/or the receiver side can be exploited, either as instantaneous (short-term) information obtained through feedback or channel estimation or as statistical information (long term) based on the moments of the channel.

Regarding the degree of channel state information (CSI) at the transmitter, signal and coding design for MIMO systems has traditionally concentrated on two extreme cases: perfect CSI, for which multi-beamforming strategies are optimal, and unavailable CSI, for which space-time codes have traditionally been proposed. Partial CSI situations have been far less explored, and the relationship between the quality and degree of CSI and the associated capacity-achieving architecture needs to be further studied. Clearly, scalable signal processing/coding designs that adapt themselves to the degree and quality of the available CSI will surely be the optimum choice for these situations.

MIMO designs for situations with both imperfect and incomplete CSI at the transmitter have recently been proposed in the literature. Imperfect CSI refers to the case where the channel estimation presents some errors, while incomplete CSI describes a situation where the transmitter has only access to some channel information (phases, amplitude, covariance, mean, etc.) instead of its actual physical realization. We have concentrated on the later case, which will be referred to as "partial CSI" availability.

There is currently a large amount of literature proposing optimal and suboptimal transmit architectures for partial CSI availability. In general terms, partial CSI might be acquired either from a feedback link (as is the case in frequency division duplex systems, FDD) or exploiting the electromagnetic reciprocity properties of the channel (in time division duplex systems, TDD). Either way, there are several ways of modelling the lack of total CSI at the transmitter. For example:

- Assuming that only some statistical parameter related to the channel is known at the transmitter. This type of assumption is quite reasonable in fast fading channels where delay associated with the return link would render any channel information completely outdated. The model also makes sense in MIMO channels with strict limitations in the feedback channel capacity, because the amount of information that must be fed back is significantly lower than in a situation where complete CSI must be instantaneously available. Usually, two different cases are considered regarding the type of statistical information available at the transmitter: the mean value of the channel, or its covariance matrix [111]. In both cases, the transmission strategy is usually determined by maximizing the ergodic capacity.
- Assuming that only part of the instantaneous information of the channel is available [109]. This situation might arise in systems where the feedback link capacity is severely limited, or in transmission schemes where reciprocity only holds for some channel characteristics (and not all). Typical examples are MIMO architectures designed with amplitude or phase channel availability. For example, in time division duplex (TDD) mobile communication systems, it is common practice to exploit electromagnetic reciprocity between uplink and downlink channels. However, in practice uplink and downlink channels are seen through different radiofrequency chains, and this usually destroys the uplink/downlink channel reciprocity. In practice, calibration of the amplitude response of the different radiofrequency chains is relatively easy, while calibration of the phase of their

response becomes substantially more complicated (due, for example, to different lengths of the tracks between the oscillator and the different mixers). Hence, in such architectures it seems reasonable to assume that the transmitter has perfect knowledge of the channel amplitude only, while the phases are independent and identically distributed. The optimal transmission schemes in this situation needs to be further investigated.

- Assuming that the design of the transmit architecture is carried out at the receiver. An example of this situation can be found in [110], where the optimum transmit antenna weights for a MIMO Bell Labs space-time (BLAST) architecture are designed at the receiver and fed back to the transmitter.
- Modelling the channel response with a parametric model. For example, by exploiting the angular characteristics of the channel impulse response, one can significantly reduce the amount of information that needs to be available at the transmitter. A similar approach is used in the FDD standard of UMTS to implement a downlink beamformer.

1.2 Advanced Receiver Structures

High data rate multiuser wireless communications systems can be achieved with the combination of multiple antenna systems and code division multiple access (CDMA). The capacity of multiple transmit and receive antenna systems increases linearly with the number of antennas on rich scattering channels [117]. Existing literature suggests the exploitation of this increased capacity for multiuser systems by means of direct sequence (DS) code division multiple access (CDMA) [118][119][120]. Furthermore, multicarrier CDMA (MC-CDMA) has also been proposed for MIMO systems, offering significant capacity increases as well (e.g. [121][122]). A third form of user discrimination is possible in MIMO systems, namely SDMA.

The combination of CDMA and MIMO is a problem of practical interest for 3G systems and for future generation wireless as well. Given the many options that a designer has to build such system, it is of practical interest to investigate the tradeoffs for fading dispersive channels, such as rate versus diversity, or performance versus receiver complexity. In addition, a relation or comparison between different CDMA ‘flavors’ can also facilitate the design process. For example, MC and DS CDMA have been compared for single antenna systems by many authors, but such comparisons focused on performance results, which often depend on factors not intrinsic to MC or DS CDMA, causing disparity in the results obtained. A way to relate and compare MC and DS CDMA is by means of time-frequency duality, which provides a framework to compare these two CDMA variants in time and frequency dispersive MIMO channels. Such analysis has found applications in matched filter and spreading sequence design, and can be easily extended to consider SDMA as well.

There are also additional areas of interest regardless of the choice of a particular CDMA technology, such as:

- Advanced receiver design; in particular, iterative multiuser detection.
- Channel estimation, which is specially challenging for MIMO CDMA given the large number of parameters defining the multiuser channel.
- Integration of low rate/high rate, single/multiple antenna terminals in a heterogeneous, scalable CDMA network.

1.2.1 Principles of Multi-user Pre-equalization

An important drawback of transmission schemes based on CDMA is MAI (Multiplei Access Interference) arising from an imperfect separation of user’s signals. Efficient MAI mitigation at the receiver involves MUD techniques, which are generally based on knowledge about the interfering users [189]. However these techniques generally require an increased complexity and power consumption that may not be tolerable in mobile terminals. Pre-equalization with CSI knowledge at the BS represents thus an alternative solution; here the signals are prefiltered at the BS transmitter so that the MAI level at each terminal is reduced. In some proposals the prefiltering operation may take into account the data symbols of the different users, thus leading to a nonlinear solution [186]. However due to the complexity of the nonlinear approaches, most of the proposals have dealt with linear schemes [105][106][107] In the multi-antenna case, pre-equalization at the basestation can benefit from the spatial dimension, which corresponds to additional degrees of freedom, which leads to very efficient MAI mitigation.

A multiuser scenario with a single transmit antenna, pre-equalization (also sometimes referred as pre-coding), was considered among others in [183], where it was shown that a ZF pre-coding at the transmitter together with SUD (single user detection) techniques at the receiver can achieve the same performance as a conventional system with MUD at the receiver. In other words the complexity of MUD can be shifted to the transmitter where the complexity and power consumption constraints are not so severe, without penalty loss.

In multi-antenna transmission over flat fading channels, pre-equalization only explores the spatial dimension, and for a single user it can be seen as a transmit diversity scheme. This diversity scheme outperforms other spatial diversity techniques by ensuring that the signals transmitted through the different antenna branches add coherently at the receiver [187]. Multiuser spatial pre-equalization with such channels is similar to the classical beamforming approach, and thus provides an effective separation of user's signals [188] .

For frequency selective channels, combining time or frequency pre-equalization with spatial pre-filtering yields a two dimensional pre-filtering scheme. While pre-equalization for a single antenna does not provide dramatic improvements other than the complexity transfer from the receiver to the transmitter, pre-equalization with multiple antennas can provide a substantial gain compared to MUD techniques even when the CSI is imperfect [190]. In single carrier systems, the pre-equalization is generally performed in the time and space domains (e.g. [182]), but frequency domain approaches exploring the frequency redundancy in DS-CDMA systems have also been proposed [45].

For multicarrier systems, the use of pre-equalization with multiple antennas has been considered in [46] under a zero-forcing criterion and in [184] by considering the maximization of the SINR at the terminal side (under some simplifying assumptions on the multiple access interference structure in order to obtain a tractable problem).

1.2.2 Channel Estimation

The development of next generation high data rate wireless communications has revealed the demand for efficient/optimum utilization of all the available resources as well as the elimination of the impairments caused by the communication chain. Multicarrier (MC) transmission, with OFDM being a successful example of achieving high data rate communications on practical systems –e.g. WLAN standards: HIPERLAN and IEEE 802.11-, is an efficient technique in combating distortions due to multipath propagation in mobile communications and capable of achieving high spectral efficiency. Moving a step further, MC-CDMA is a system that incorporates the CDMA concept in a multicarrier architecture by spreading in the frequency domain the information of each user, thereby making it possible to decode multiple users simultaneously [125]. MC-CDMA technology is expected to be adopted in future communication systems incorporating inner/outer coding, interleaving in time and frequency domain, perfectly orthogonal codes, and equalization based on various schemes (EGC, MMSE, TORC, etc) [126]. Such a system is more effective in both eliminating frequency selectivity and allowing better spectrum utilization. Furthermore, it has to be noted that the receiver complexity is reduced since advanced rake receiver stages are not necessary. The employment of MC-CDMA for mobile multi-user communications has become an active field of research since 1993 [127]. Up to now, most of the research has been focused on data detection techniques and system architectures for both uplink and downlink, and little attention has been paid to the influence of non-perfect channel estimation.

However, the accuracy of channel estimation is indeed a key point on the design of an efficient (MC-CDMA) system. In systems which employ multiple element antennas at the transmit and/or the receive ends, complexity issues should also be considered. Thus, a balanced accuracy-complexity tradeoff is essential depending on the application environment that the system is targeting. The channel estimation stage is of vital importance in the performance evaluation of the whole system and its compromise between optimality and implementation restrictions is a very challenging issue. Optimality can be establish according to multiple criteria, e.g. in terms of quality of the attained channel estimate in MSE terms (signal processing approach), based on low complexity criteria (budget approach), or based on a system design that maximizes the data throughput (information theoretic approach). The third approach is of major importance, since for a given propagation channel it gives an upper bound on the maximum achievable data rate that can be reliably transmitted, i.e. the channel's capacity [128].

Next, we review channel estimation mechanism for wireless mobile communications, placing special emphasis on multicarrier schemes.

There are various ways of performing channel estimation, depending on the parametric model choice, the use of the channel's frequency and/or time correlation properties, the blind semi-blind or training nature of the method, as well as its adaptability [129]. Training based estimation techniques are common in the most communication systems, where the transmitter sends a known signal to receiver (pilot) in order to allow for channel estimation or equalizer training. Blind estimation, on the other hand, avoids training overhead by completely relying on the statistical properties of the transmitted signals that known to the receiver (like cyclo-stationarity, or specific pulse shaping effects).

There is a generic trade-off when it comes to the model used for channel estimation. Channel estimation based on complete parametric models usually offers better performance due to the fact that the number of parameters to be estimated is smaller, but suffers from model mismatch in cases where mixed propagation conditions are encountered. The use of a more generic model will improve the robustness of the estimator but will result in higher estimation errors due to the increased number of parameters being considered. In some situations, for instance in very rapidly varying scenarios, it might be more convenient to estimate the channel statistics rather than its actual realization at a given time instant. The computation of the channel's time and frequency correlations can be done either in time or in frequency domains (1-D estimators), or jointly, what gives rise to the so-called 2-D estimators.

For multicarrier systems, whether single-carrier (OFDM) or multi-carrier (MC-CDMA), the estimation techniques can broadly be classified into:

- Pilot based channel estimation, where known pilot symbols are multiplexed within the data.
- Blind approaches which generally rely on some statistical properties of the transmitted signal [191][192][193][194]. These approaches are obviously more efficient in terms of the spectrum usage since they do not introduce any overhead for pilots but suffer from long convergence time and high computational effort. Furthermore for an adequate performance they might typically require knowledge of the channel order, [195][196] which for unknown channels must also be estimated [197].
- Hybrid structures, where the pilot based estimates are aided by the data detection. Indeed, once a decision has been taken on a data symbol, this symbol can be fed back to the channel estimation unit and used for a refinement of the estimation in iterative approaches [198] [199][200][201]. In such a case we have two design options: the channel estimation unit is designed as a standalone but uses the decided symbols as the correct ones, or may have a joint design channel estimator-equalizer-detector.

1.2.2.1 Pilot-Aided Estimation

Coherent detection and soft decision decoding in receivers operating in fading radio channels require channel state information. The basic principle of pilot symbol aided channel estimation is the multiplexing of pilot symbols into the data stream. Particularly, transmission systems with MC modulation allow the estimation of the time varying channel transfer function in both the time and the frequency domain by inserting pilot symbols on different subcarriers in frequency and different intervals in time, with the intention to estimate the channel transfer function. Pilot symbols can be arranged either rectangular or diagonal or randomly within an OFDM block [130]. Extensive simulation results presented in literature reveal that channel estimation schemes with either rectangular or diagonal distributed pilot symbols exhibit similar performance and outperform schemes with randomly distributed pilot symbols [131]. The distance in frequency and time direction depends on the characteristics of the propagation channel, since it has to be a compromise between a reliable estimation and a minimum overhead [132]. Uplink channel estimation is more challenging even when pilots are used (non-blind) than downlink particularly because the user's signals go through different multipath channels and the system is multi-access. When the spreading sequences employed to spread the information over the whole bandwidth are aperiodic, blind (subspace) based approaches [133] developed in the context of DS-CDMA are not applicable. This weakness motivated the study [134] of channel estimation problem for MC-CDMA systems using aperiodic spreading codes.

The 2 dimensional pilot symbol aided channel estimation operates in two steps. In the first step, the initial estimate of the channel transfer function at positions where pilot symbols are located is obtained by dividing the received pilot symbol by the originally transmitted pilot symbol. In the second step, the final estimates of the complete channel transfer function belonging to the relative OFDM block are obtained from the initial estimates by a 2-D interpolation or filtering. The 2-D filtering is based on the 2-D Wiener filter in which achieves the minimum mean square error of the channel estimation through the orthogonality principle [135].

Since 2-D Wiener filters tend to have a large computational complexity, a good trade-off between performance and complexity is the use of two cascaded 1-D Wiener filters, the first one in frequency direction and the second one in time direction [136]. The filter implementation of either 1x2-D or 2x1-D has been based mainly on FIR architecture, although IIR could potentially be used.

It is important to note that, in the majority of published work [137] in the synchronous downlink of the MC-CDMA systems, the pilot symbols of the active users are transmitted simultaneously on the same positions. Thus, the total available energy of the pilot symbols in an OFDM block which can be exploited per user increases with increasing number of users. Another attractive option is the transmission of the pilot symbols with increased energy (boosted pilot symbols) [138]. The boosting of pilot symbols achieves better estimates of the channel but reduces the average SNR of the data symbols.

1.2.2.2 Channel length utilization

In the receiver design, channel estimation has been approached either as a separate stage or as a part in a joint operation with symbol detection. In the separate case, the channel estimation techniques of the single-user receivers can be applied. In general, a complex channel coefficient FIR estimation filter can be divided in two parts: prediction and smoothing [139]. Since the past samples are always available for channel estimation, the channel estimation filter which uses only past samples for complex channel coefficient estimation is characterized as linear predictor. In the case that the estimator uses both past samples and the current sample it is characterized as linear filter, whilst in the case of exploitation of past and future samples the filter is characterized as linear smoother. Furthermore, the channel estimator can be incorporated in an iterative procedure.

1.2.2.3 Blind Estimation

Since pilot symbols reduce spectral efficiency, blind estimation schemes have received a lot of attention. Most research has focused on methods based on higher order statistics, which converge very slowly and are thus unsuitable for mobile environments [140]. A breakthrough on this shortcoming has been done by the use of cyclo-stationary statistics, where fast convergence is achieved through the use of second order statistics, and the phase blindness has been resolved based on hidden periodicities of the transmitted signal that are known to the receiver. Moreover, phase ambiguity that is introduced in the channel estimate, has been overcome by the use of at least one reference symbol. Phase ambiguity in blind channel estimation has been overcome efficiently by incorporating modulation schemes with asymmetrical symbol arrangement on the constellation map. Another, recent approach to overcome the above shortcoming is the combination of two modulation schemes and the utilization of maximum likelihood principle.

1.2.2.4 Channel estimation in MIMO Architectures

High data rates in mobile communications, typically nearing 1Gbps [141], can be achieved through the use of multiple antennas at the transmitter and the receiver (MIMO architectures). Estimation of MIMO channels is an open research area, where the performances of the existing estimation methods designed for the SISO scenario have to be evaluated and adapted to the new architectures. For example, in V-BLAST architectures, the MIMO channel estimator has to provide the receiver with accurate information of all sub-channels to ensure a reliable suppression of self-interference within a successive interference cancellation (SIC).

Recent research results have proposed the use of super-imposed pilot (SIP) training for channel estimation [142]. The transmission of a block is divided into two modes. The first mode is the SIP mode in which pilot symbols are superimposed (added to) low-power data symbols. The second mode is the pure data mode in which only a block of information symbols is transmitted. It should be noted that such an approach is a generalized scheme of the time-multiplexed conventional pilots and the overlay pilots.

In a large amount of publications [143] the effect of the estimation errors have been evaluated when either the estimates are available at the receiver only, or when they are fed back to the transmitter. Furthermore, some elaborate information-theoretic studies have been performed analyzing different training schemes [144] and parameter optimization targeting to maximization of lower bounds on the open loop MIMO capacity.

The need for sophisticated channel estimation for MIMO systems is determined by the fact that, the more transmit antennas are applied in a communication system, the more channel coefficients need to be estimated. Considering a constant pilot power which is independent from the number of transmit antennas, the power of pilot signal transmitted from a specific antenna reduces with increasing number of antennas. Hence, less pilot power is available for the estimation of a channel coefficient leading to a worse signal to noise ratio for the channel estimates. This highlights a general problem of MIMO-techniques: the MIMO capacity gain can only be reached if reliable estimates of the channel coefficients are available at the receiver.

In general, most of the basic concepts developed for SISO channels can be applied with MIMO architectures, with the exception that the complexity is increased by the number of channels one needs to estimate. For the uplink MIMO system with K active users, M antennas at the base station and N at the mobile, we need to estimate $K\times M\times N$ different radio channels. For example considering the conventional pilot based method based on an MMSE criterion, we have $K\times M\times N$ matrix inversions with dimension $Np\times Np$ for an OFDM or MC-CDMA scheme using Np carriers, which is computationally very intensive.

For pilot-aided channel estimation techniques, the channel estimator exploit pilot symbols from each transmit antenna, which are known by the receivers. These pilot symbols must be orthogonal with respect to each and designed to decouple the inter-antenna interference [204]. A common approach is to use orthogonal sequences at the different transmit antennas. However, orthogonality is not sufficient for good parameter estimation of dispersive fading channels. Instead, the optimal training sequences for different training antennas are shown to be local orthogonal, i.e., for any starting position they are orthogonal over the minimum set of elements. In [210] the authors present a criterion for optimum pilot-sequence design for MIMO-OFDM. Using this design criterion they can design training sequences that not only optimize, but also simplify the channel estimation during the training period at the expense of a negligible performance degradation.

In [205] an optimized channel estimation concept is considered for correlated MIMO channels that adapts the pilots sequences to the prevailing correlation properties of the channel. Its application was demonstrated with standard MIMO signal processing algorithms, exhibiting a significant gain compared to standard MMSE channel estimation. The adaptive transmit processing of the pilot sequence relies on the long-term statistics of the channel which have slow variations over time.

Other enhanced channel-estimation technique for MIMO-OFDM was proposed in [206] that reduces the mean square estimation error using a cyclic comb-type training structure. In the proposed cyclic training structure, all types of training symbols are transmitted cyclically at each antenna. At the receiver, the channel frequency responses that are estimated using each training symbol are averaged with weights obtained from the corresponding mean square errors. Computer simulations showed that the proposed cyclic training structure gives more signal-noise-ratio gain than the conventional training structure.

As mentioned above, increasing array size requires a large overhead for pilot-based channel estimation schemes, thus limiting the overall spectral efficiency. In order to alleviate the need for training sequences, thereby achieving a much desired bandwidth gain, blind channel estimation, that is, estimate the channel response using solely their output statistics, is desirable. Among the various algorithms reported in the literature, second order statistics based algorithms are the most attractive due their special properties [203]. The subspace method [203], has a simple structure and achieves good performance for MIMO systems, but requires precise knowledge of the channel order, which is impossible in practice. Estimation of the channel order is significantly more difficult with MIMO than in SISO systems, because not just one order but many orders are needed to be estimated. Due to noise, it is impossible to obtain precise channel orders. However, channel order upper bounds can be obtained from some priori knowledge of propagation conditions in wireless communications. In [209] a blind MIMO channel estimation method tolerating order overestimation is proposed.

The estimation of flat-fading MIMO channel matrix is approached in many publications by semi-blind algorithms that are based on the decomposition of the channel matrix into the product of a whitening matrix and a unitary matrix [148]. The whitening matrix can be estimated blindly from the received data whilst the training data are used for the extraction of the rotation matrix. For totally blind MIMO channel estimation, the use of a linear non-redundant block pre-coding scheme that introduces a unique structure to the transmitted symbols has also been proposed. At the receiver the MIMO channel is blindly estimated based on cross-correlation operations by utilizing the a priori knowledge of the pre-coding structure [149].

In conclusion estimation for MIMO channels is an open research area, where the performances of the existing estimation methods designed for the SISO scenario have to be evaluated and adapted to the new architectures, as well as the methods with witch the MIMO channel estimation should be taken into account [207].

1.2.3 Interference rejection at the receiver

One of the main goals of wireless network research is to design a network that provides high-data rates for many users in a limited spectrum taking into account the self-interference in the system. One means for achieving this goal is to develop receivers that are capable of operating with extremely signal to interference ratio i.e. interference rejection receivers. Such receivers can employ one of several possible strategies but need to utilize some unique property of the desired and interfering signals in order to be able to separate the two. Such properties can exist of the modulation format, training sequences, pilot tones, constant modulus etc. Based on this knowledge the receiver may then exploit it by employing least-mean-square-error methods, joint detection methods, adaptive filters, neural networks, subspace methods etc. A large number of references to work in this area may be found in page 6-7 of [124].

The receiving problem is conceptually simple as it deals with retrieving information from a given set of data and there are many readily available theories for solving the problem (e.g. estimation-, detection-, filtering-theory.) Note also that since most digital systems are based on buffer processing. The received buffer can be processed in several passes and information derived at the end of the burst (e.g. channel impulse response) can be used in the beginning of the burst i.e. employing in some sense non-causal possibilities. This is in contrast to interference rejection at the transmitter.

1.3 Re-configurable-Adaptive Transmission Schemes

1.3.1 Adaptive Modulation and Coding

In order to utilize the wireless channel in the best possible way for data throughput and achieve high data rates, adaptive modulation and coding (AMC) is currently being used in the 3GPP standard, including both UMTS and CDMA2000 implementations. The factors that govern the achievable performance are channel conditions, power and AMC philosophy based on available information, as well as channel and signal-to-interference ratio (SIR) estimation accuracy. The ultimate goal of current high data rate transmission schemes within the WCDMA context is to adapt the current channel conditions by selecting the most suitable AMC scheme, leading to the highest throughput level. In addition, current research on MIMO performance has added another parameter in the search for optimal AMC schemes.

In [155], there is a study of the BER performance of two transmit diversity techniques in MIMO systems, i.e. space-time coding (trellis and block codes), and BLAST (Bell Labs Layered Space-Time Architecture). It compares the two techniques in a system with two transmit antennas, using QPSK modulation. The results show that space-time block codes outperform all the other techniques examined.

In [156], some techniques of adaptive transmission and diversity-combining are examined, in terms of channel capacity. In particular, the first technique refers to the optimal power and rate adaptation, the second considers constant power with optimal rate adaptation and the last uses channel inversion with fixed rate. The second method offers a small increase in the capacity of the channel compared to the first one, and channel inversion suffers the largest capacity penalty, which decreases though as diversity increases. The trade-off between the small complexity of channel inversion and the higher capacity obtained by the other methods is examined. The results are for Rayleigh channel and a system that uses MQAM modulation.

In [157], we find a study of the three basic elements of link level simulation models for UMTS Terrestrial Radio Access Network: channel estimation, SIR estimation and power control method. These parameters are examined in UTRA TDD and FDD modes (uplink and downlink), and their description is given in a form of detailed equations.

A channel estimation technique that uses time multiplexed pilot symbols is presented in [158]. This scheme uses Weighted Multi-Slot Averaging (WMSA), and is examined for coherent Rake combining. The performance measure is in terms of BER, in multipath Rayleigh fading environments. According to the simulation results, when fast Transmit Power Control is also applied, the gain in Eb/No achieved by the proposed technique is about 0.8 dB.

In [159] the authors propose an open loop transmit antenna diversity technique named Space Time Transmit Diversity (STTD). STTD outperforms both Time Switched Time Diversity (TSTD) and Orthogonal Transmit Diversity (OTD), as it offers improved Link Margin, backward compatibility with no antenna diversity schemes, robustness to imperfect channel estimation and maintaining a less than one time slot roundtrip power control loop delay. These parameters make this open loop transmit diversity scheme a good choice for WCDMA.

A closed-loop power control scheme for CDMA systems is proposed in [160]. It uses both fixed-step and adaptive-step power control algorithms and works with RAKE receivers. The system that is presented estimates the received power and the bit energy-to-interference power spectral density ratio. Rayleigh and Rician fading channels were considered. According to the results, when a RAKE receiver with less than 2-taps is used, the performance of adaptive-step-size power control scheme is only slightly better than the fixed-step-size one. For a 3-tap RAKE receiver, the gain by using adaptive-step-size power control scheme is about 2.0 dB for Rayleigh fading channel and 1.5 dB for Rician fading channel with a K-factor of 6dB, in terms of Eb/Io.

1.3.2 Interference Rejection at the transmitter and associated feedback

In contrast to the straightforward receiving problem, interference suppression at the transmitter is much more involved e.g. the transmission can never be performed in any way non-causal as in the receiver as described above. As the selection of e.g. transmitter weights at any transmitter will change the interference level at all receivers. Furthermore, to be able to suppress the interference, the transmitter must have some form of knowledge of the transmission channel of the co-channel users. Note that this is challenging to get this information even for the desired user, see Section 1.1. Even knowing the existence of the co-channel users may be difficult think of e.g. packet data. This implies that such features must rely heavily on the possibilities made available by uplink-downlink reciprocities in terms of propagation, signalling channels or carefully tailored feedback schemes. It may be felt that the transmitter is not the place to attempt interference rejection. However, assuming that the downlink is the link that requires the highest data-rates, it is attractive to place the complexity at the transmitter i.e. the base-station due to the small multiplicity of base-stations as compared to mobile-stations.

Work in this area has been done some ten to five years ago in papers such as [212],[211],[47],[49], then focused on voice applications and second generation standards (more references can be found on page 7 of [48]).

The largest gains for the interference rejection at the transmitter can be expected for very slowly varying channels. Channel variations caused by objects in the environment (fans, cars, trees, people) together with phase and amplitude drifts in transmitter and receiver chains implies that there will never be a completely stationary channel. To address this issue it is first necessary to find the Doppler rate of channels in the applications with limited movement and how those channels can be exploited using feedback. Such an investigation must begin with channel measurements as there does not exist readily available channel models for such cases - to the extent of the knowledge of the author. It is also important to consider how it would be possible to obtain channel knowledge of co-channel users in data-centric wireless networks including other-cell co-channel users in order to facilitate interference suppression at the transmitter.

Basic work in this direction was done in [60], where a strategy which generalizes any single-link MIMO scheme (with channel knowledge at the transmitter and receiver) to take into account the interference. To be implemented as is global knowledge of all channels in the system is needed in the base-station.

The transmission scheme described in [60] has been adapted to the time division duplex (TDD) case in [61]. A special "pilot mirror phase" is introduced was introduced in the MAC-frame. During the pilot mirror phase the mobiles transmit in uplink using the weights they are going to use during reception in the downlink traffic phase. This enables the base-stations to adapt their transmission weights with nulls in the directions of co-channel users. In the subsequent downlink phase, the mobiles updates their weights based on the actual interference situation. Thus, the base and mobile-station weights are updating in an alternating fashion.

1.3.3 Classically used Space-Time Codes

In standards where multiple antennas are used at the access point (or BTS) and/or at the terminal ends, commonly the most often used schemes are

- The Alamouti code for 2 transmit antennas or orthogonal designs for more than two antennas.
- The SDM (Spatial Division Multiplex) scheme also known as VBLAST
- Beamforming

As beamforming is not a space-time code and requires a perfect knowledge of the channel at the transmitter end. The two other techniques (orthogonal designs and SDM) remain now in all wireless standards releases employing multiple antennas. These standards are currently related to 3GPP, IEEE 802.11n and IEEE 802.16e. What are the main advantages and drawbacks of these two schemes? In fact, these schemes are complementary as the advantages of the first scheme are the drawbacks of the second one and vice versa. In order to quantify that, we must introduce two quantities:

- The diversity gain
- The multiplexing gain

The diversity gain d is related to the reliability of the system as it can be shown that on a Rayleigh fading channel for a sufficiently large value of the signal to noise ratio, the error probability varies as the signal to noise ratio to the power $-d$. So, the higher the diversity gain is, the better the reliability of the system is.

The multiplexing gain is related to the data rate that the system can convey on the MIMO channel. By doing some analysis of the channel in terms of information theory, it can be shown that the capacity of the MIMO channel is roughly equal to the capacity of a single antenna channel times a factor r which is called the multiplexing gain.

In fact, there is a tradeoff between the diversity gain and the multiplexing gain. We cannot increase these two gains at the same time. But on MIMO channels, it can be shown that the maximal diversity gain that can be achieved is equal to $n_t x n_r$ and the maximal multiplexing gain is equal to $\min(n_t, n_r)$ where n_t and n_r are respectively the number of transmit and receive antennas.

The Alamouti code has lots of advantages. It is easy to decode, it achieves the maximal diversity gain of the system, but its maximal multiplexing gain is equal to 1. Since the number of transmit antennas to which it corresponds is equal to 2, then that means that this code is optimal when the number of receive antennas is equal to one. But as soon as the number of receive antennas is larger than one, then the performance of this code is not so good especially at high spectral efficiency. For example, on the IEEE 802.11n standard, we could use a spectral efficiency equal to 12 bits per channel use. But this is not for the Alamouti code as it would imply the use of a 4096-QAM constellation (in the standard, only a 64-QAM constellation is used. Moreover, for more transmit antennas, the maximum multiplexing gain is lower than one and this problem becomes more important.

At the opposite side, we find the SDM scheme. The multiplexing gain is maximized ($\min(n_t, n_r)$), but the diversity gain is only equal to n_r instead of $n_t \times n_r$. Moreover the decoder is not so simple as with the Alamouti code as the ML decoder should be based on sphere decoding for example and the MMSE decoder exhibits performances that are not so good.

The diversity-multiplexing gain tradeoff

We claimed above that it is impossible to increase both the diversity gain and the multiplexing gain. In fact, there is a tradeoff between these two values. The maximal achievable tradeoff $d(r)$ is given for the MIMO quasi-static channel (the channel does not vary during the transmission of a codeword) by a piecewise linear curve joining the points $d^*(k)=(n_t-k)(n_r-k)$ where k is any integer between 0 and $\min(n_t, n_r)$. For example, for the 2 transmit antennas and 2 receive antennas channel, Figure 1 gives the diversity/multiplexing gain tradeoff achieved respectively by the Alamouti code, the SDM scheme and the optimal tradeoff of the channel which can be achieved by a new code: the Golden Code.

The Golden Code

This code has been discovered quite recently (2004) [71][87] but its unpreceeding performances makes it a serious candidate for wireless multiple antennas channels. It has already been standardized for the IEEE 802.16e standard in September 2005 and Motorola supported it for standardization in the IEEE 802.11n standard. This code is in fact a linear dispersion space-time block code with block length 2. It is optimal when the number of transmit antennas is equal to 2 and the number of receive antennas is 2 or more. It has numerous remarkable properties, has a maximal multiplexing gain equal to 2 and diversity gain maximal. Since it can be seen as a linear unitary pre-coder followed by a SDM on two channel uses, it also preserves

the channel mutual information. Moreover, since its minimum determinant does not depend on the spectral efficiency of the used QAM constellation (it is the Non Vanishing Determinant property), then we can prove that this code achieves the Diversity/Multiplexing gain tradeoff of the MIMO channel.

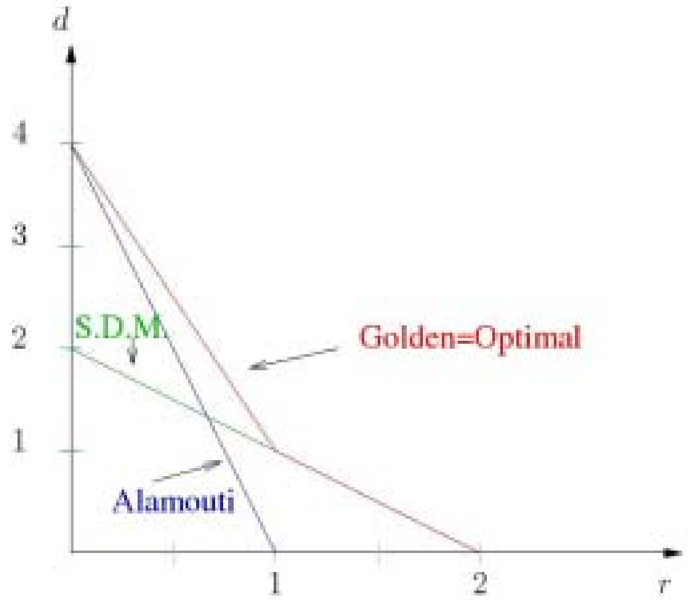


Figure 1 Diversity/Multiplexing tradeoffs.

The only drawback of this code is its decoder which is less simple than the linear combiner of the Alamouti code. Since the Golden code is a linear code, then we can decode it by using the sphere decoder [76] or some variants (such as the Schnorr-Euchner decoder [90]) which are also ML decoders. Of course, a MMSE(DFE) detector may be used despite of its poorer performance.

We can see in Figure 2 the performance of the Golden code compared to the Alamouti code and the SDM for 2 transmit and 2 receive antennas, for the same spectral efficiency on a quasi-static Rayleigh fading channel. Figure 3 shows the same curves but when the number of receive antennas is equal to 6. The Alamouti code suffers from its too low multiplexing gain (1 instead of 2). The SDM suffers from its too low diversity gain (2 or 6 respectively instead of 4 or 12 respectively).

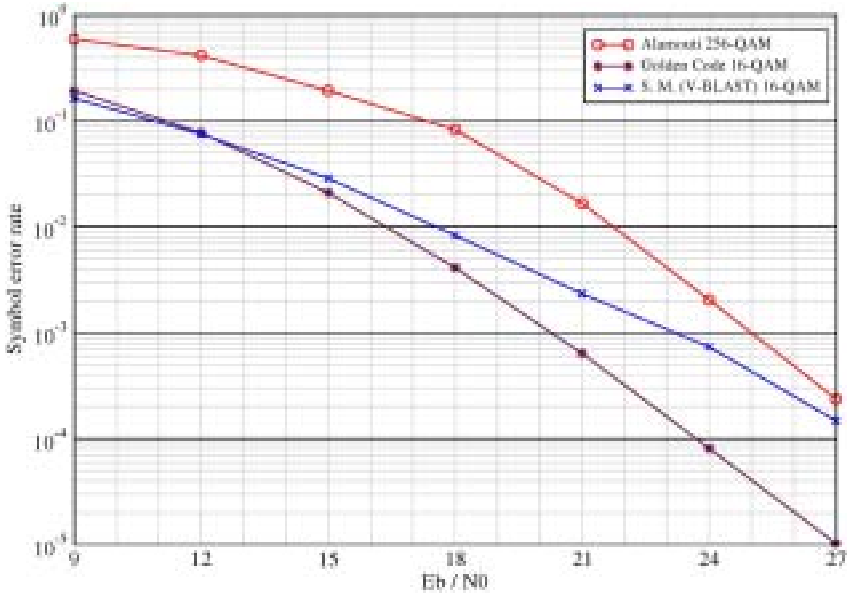


Figure 2. 2 transmit and 2 receive antennas, 8 bits spectral efficiency.

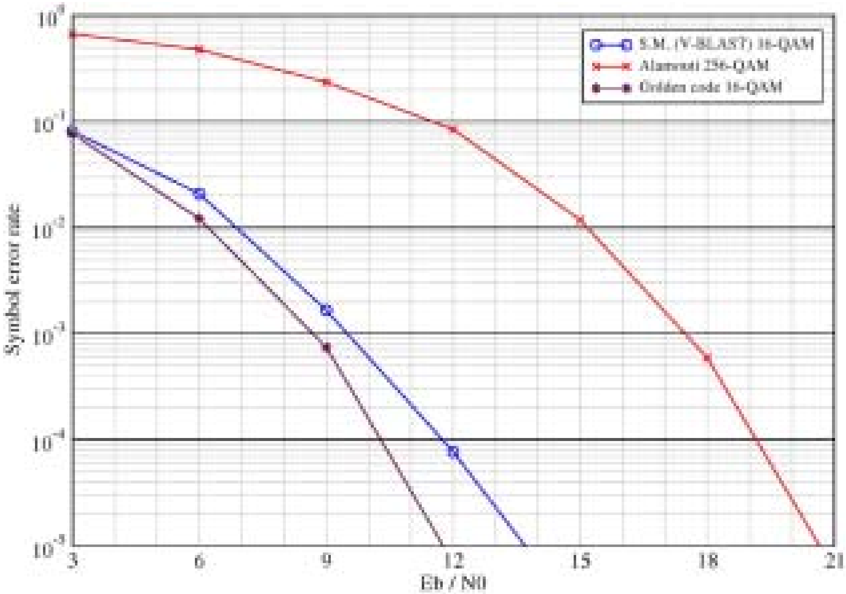


Figure 3. 2 transmit and 6 receive antennas, 8 bits spectral efficiency

1.3.4 Adaptive/Robust Linear Pre-coders

Future wireless systems are expected to offer optimized performance by achieving adaptivity to varying propagation and network conditions. For the design of re-configurable transceivers, the channel state information available at the transmitter and/or the receiver side can be exploited, either as instantaneous (short-term) information obtained through feedback or channel estimation or as statistical information (long term) based on the moments of the channel.

Linear pre-coders have been proposed in the literature, which exploit the knowledge of long-term properties of the channel (mean, correlation matrix) and optimize performance and achieve robustness with respect to antenna correlation and mobile speed. These pre-coders exploit the channel correlation matrix knowledge at the transmitter to weight the space-time block encoder so that the upper bound on Pairwise Error Probability is minimized. Different from this symbol-error-rate (SER) bound criterion, optimal transmitters can be designed to maximize the expected SNR at the receiver. The optimal design in this case can be easily proved to be a transmission in the direction of the strongest channel covariance matrix eigenvector. Therefore, the optimal solution reduces to an invariant beamformer (beam-steering vector) pointing to one direction. However, maximizing the average SNR is not equivalent to minimizing the SER. The reason is that the average SER depends not only on the average SNR, but also on higher SNR moments such as the SNR variance. Because the SER is dominated by worst case errors, the SNR variance should be small to ensure that worst cases are as rare as possible when the solution deploys only one, namely the strongest, eigen-beam. The design based on the SER-bound criterion does not achieve the maximum expected SNR, but the best compromise between the mean and the variance of the received SNR. In [123],[44] this approach is presented via a re-configurable linear pre-coder, which compensates for antenna correlation in orthogonal space-time block coded systems. The proposed technique assumes the knowledge of the long-term characteristics of the channel, namely the channel correlation matrix at the transmitter. For low antenna correlation values the proposed technique is equivalent to space-time block coding, whereas for high correlation values it is proved to be equivalent to beamforming. The block diagram of such scheme is shown in Figure 4 under a UMTS framework. For intermediate antenna correlation values the proposed technique outperforms the conventional approaches. The sensitivity of the proposed reconfigurable design to channel state information errors at the transmitter is also investigated and its robustness is demonstrated.

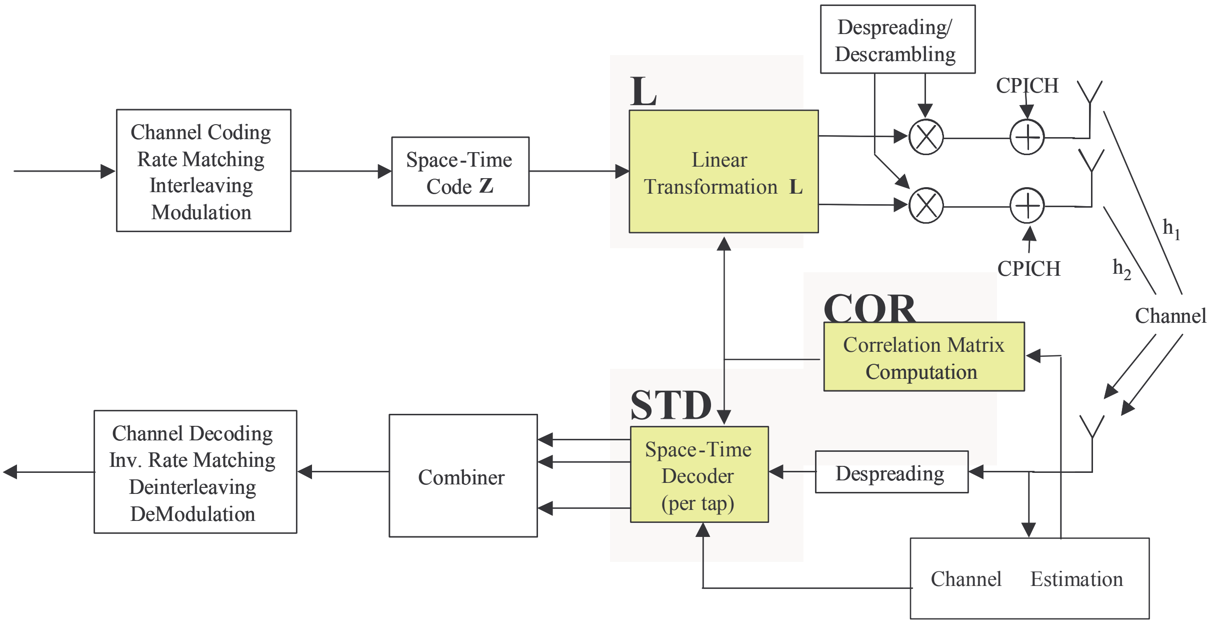


Figure 4. Transceiver architecture for UMTS DL implementing re-configurability to antenna correlation.

1.4 Jointly Optimised MIMO Transceivers

1.4.1 Antenna Selection Techniques

One of the main purposes of Task 4 in WP 2.2-3 of the ACE project has been to employ antenna selection in MIMO systems and extract new antenna selection algorithms for them. The idea of antenna selection is to use only a subset of the available transmit and/or receive antenna elements, reducing the number of RF chains used, while meeting specified criteria. In this way, two basic and desirable advantages are exploited: complexity reduction and cost reduction. Additional antenna elements are usually cheap and the additional digital signal processing is becoming less of a problem, since digital processing becomes more and more powerful. However, RF chain components, like LNAs, downconverters, and analog-to-digital converters are a significant cost factor. This leads us to the conclusion that RF chains must be reduced, which can be achieved by choosing the "best" L out of N antenna elements of a link side.

Antenna selection can be applied to MISO, SIMO or MIMO systems and can refer to the transmitter side, the receiver side or both (Hybrid-selection schemes).

When using multiple antenna elements at both link ends, there are three basic ways in which they can be exploited:

- Exploit the diversity effect, which means that transmit and receive diversity are used purely for link-quality improvement. All transmit antenna elements transmit streams of the same information. The antenna selection approach in this case is called "Hybrid-selection / Maximal Ratio Combining (HS-MRC)" or sometimes also "Generalized Selection Combining" (GSC) and apart from MIMO it can be employed to SIMO and MISO systems as well.

- Multiple elements at both link ends are used for “spatial multiplexing”. In this case, transmit antenna elements transmit different, independent symbol streams (or partially correlated streams), exploiting the formation of independent spatial communication channels. The antenna selection approach, here, is called “Hybrid-Selection/MIMO” (HS-MIMO).
- The communication system, to which antenna selection is applied, is a “Space-Time Coding” System. This means that Layered Space-Time Coding strategies are used in order to approach the theoretical capacities of a MIMO system (BLAST systems). In this case, independent (or partially correlated) symbol streams are transmitted from the transmit antenna elements too.

Three types of selection combining are distinguished (when multiple antennas are used for diversity purposes):

- **Maximal Ratio Combining (MRC):** The SNR of the optimal ratio combiner is the coherent sum of the SNRs of each individual diversity branch.
- **Conventional Selection Combining (CSC)**: The CSC combiner selects the signal from that diversity branch with the largest instantaneous SNR.
- **Generalized Selection combining (GSC) or Hybrid-Selection/MRC (HS-MRC)**: The GSC combiner chooses the L largest signals (instantaneous SNRs) out of the N total diversity branches and then combines them coherently.

Performance of GSC is superior to the performance of CSC and can be very close to the performance of MRC.

Two kinds of antenna selection are distinguished in the literature:

- *‘Deterministic Antenna Selection’*: Sets of antenna elements are selected per channel instance (realization), with computation of optimal sets performed every time the channel changes.
- *‘Statistical Antenna Selection’*: MIMO antenna sub-set selection is based on second-order channel statistics, when spatial multiplexing or space-time coding techniques are used over the wireless link.

‘Statistical Selection’ is preferable to ‘Deterministic Selection’ in cases where the latter may not be feasible, due to delays in feedback (in FDD systems) or large ping pong times (in TDD systems).

1.4.1.1 Criteria for Optimal Antenna Subset Selection

Several criteria are used in the literature depending on the considered transmission-reception scheme, or the type of the receiver employed. The most widely used criterion for the selection of the “best” subset of antenna elements is *capacity maximization*. This means that we choose that subset of antenna elements, for which the capacity of the system (or outage capacity) is the highest among all capacity values achieved by any other possible antenna subset.

Another criterion that is often used for optimal antenna selection is *maximization of the SNR* (instantaneous or average) of the reduced-complexity system.

In cases of statistical antenna selection, the criterion that is mostly used is *minimization of the average symbol error rate* or *minimization of the average symbol error probability*. This is interpreted into a maximization of the determinant of transmit and/or receive covariance matrix (under certain assumed propagation scenarios).

Several propagation scenarios have been assumed and have become the basis of an extensive research on antenna selection schemes and algorithms over the last few years. Throughout all these cases, of crucial importance is the *rank* of the channel matrix, denoted here by k. If we consider a system with M transmit antennas and N receive antennas ($k<M$, $k<N$), the general idea is as follows: reduce first the number of

transmit antennas to a number equal to the rank of the channel matrix, by choosing the 'best' k transmit antenna elements (transmit antenna selection). This, in many circumstances, causes a small increase in system's capacity. Then reduce the number of receive antennas to a number not smaller than the selected transmit antennas. In this way, one can exploit all possible independent spatial communication channels of the MIMO system, leading to an achieved capacity which is close to the capacity of the full-complexity system. For further capacity enhancement, in order to reduce the performance loss due to antenna selection at the expense of an additional cost, the selected number of receive antennas shall be greater than k and smaller than M, introducing a greater diversity effect to the system, which results in a small increase in system's capacity. So there is a trade-off between cost and diversity gain. It should be mentioned, that as the number of receive antennas approaches M, additional diversity gain (and thus additional capacity increase) becomes more negligible, so it will not be worthy selecting a number of receive antennas very close to M and much larger than k, under certain cost confinements.

It is interesting to study existing techniques under a more refine criteria and maximization or minimization techniques for different channel types, single or joint link end selection, etc. New approaches based on evolutionary programming techniques are worthwhile investigating. Antenna selection could provide means for adaptive transceiver structures. This research item is in close relation with WP2.2-4 task 2 where antenna selection optimisation criteria are based on performance metrics related to upper layers and has been addressed from a cross-layer optimisation point of view.

2. Initial Know-How of the Participants

This section relates to the activity performed in the workpackage to gather the scientific know-how of the integrating partners, with the aim to identify knowledge gaps and to assist to establish collaborations between partners. The initial know-how of the partners involved in this workpackage is presented under two points of view, one comprising the scientific expertise and the second related to prototypes and test-beds implementation and development expertise.

2.1 Scientific know-how

The scientific know-how of the **Royal Royal Institute of Technology** (KTH) is described in relationship with their most recent publications related to this workpackage.

The first two references deal with a single-link MIMO scenario where the transmitter has partial information of the channel. In the first one, the bit and power load on the spatial data streams are adjusted so that the data rate is maximized given an approximate BER and an average power constraint. The second utilizes full diversity block-codes, and a weighting matrix is selected so that an upper bound on SER is minimized.

The main contribution is an approximate formula of the BER for the individual data streams. The formula is based on (but not identical to!) the well-known union bound of pairwise error probabilities. However, the union bound gives an upper bound on the joint error rate of all data streams while we consider the data streams individually.

- S Bergman, C Martin and B Ottersten. "Bit and Power Loading for Spatial Multiplexing using Partial Channel State Information". In ITG Workshop on Smart Antennas, Münich 2004.

Abstract: Using information about the channel at the transmitter can improve the performance of Multi-Input Multi-Output (MIMO) communication systems. When perfect Channel State Information (CSI) is available at the transmitter, data can be multiplexed and optimized over independent spatial channels. However, when the available channel information is imperfect or partial, crosstalk between the spatial channel is inevitable, complicating the design of the transmitted data. This paper presents a novel practical bit and power loading algorithm, Spatial Loading based on Incomplete Channel Estimates (SLICE), that enables the use of partial CSI for spatial multiplexing. An approximation for the Bit Error Rate (BER) of the spatial channels is derived that facilitates the loading. Numerical experiments demonstrate performance improvements compared with methods that do not consider the partial information available.

- George Jöngren, Mikael Skoglund and Björn Ottersten. "Combining Beamforming and Orthogonal Space-Time Block Coding". In IEEE Transactions on Information Theory, Vol 48, No 3, March 2002.

Abstract : Multiple transmit and receive antennas can be used in wireless systems to achieve high data rate communications. Recently, efficient space-time codes have been developed that utilize a large portion of the available capacity. These codes are designed under the assumption that the transmitter has no knowledge about the channel. In this work, on the other hand, we consider the case when the transmitter has partial, but not perfect, knowledge about the channel and how to improve a predetermined code so that this fact is taken into account. A performance criterion is derived for a frequency-nonselective fading channel and then utilized to optimize a linear transformation of the predetermined code. The resulting optimization problem turns out to be convex and can thus be efficiently solved using standard methods. In addition, a particularly efficient solution method is developed for the special case of independently fading channel coefficients. The proposed transmission scheme combines the benefits of conventional beamforming with those given by orthogonal space-time block-coding. Simulation results for a narrow-band system with multiple transmit antennas and one or more receive antennas demonstrate significant gain over conventional methods in a scenario with nonperfect channel knowledge.

The following two references are related to Section 1.3.2 of this document. In particular, Section 2 of the first reference sketches a solution to the problem outlined in that section, namely that of how to perform interference rejection at the transmitter in low-mobility environments. The sketched solution involves use of TDD and a feedback channel, which is tailored to be used as information in the downlink beamforming.

- P Zetterberg. "A Smart Antenna Concept for 4G and Transceiver Cost", In Proceedings of Nordic Radio Symposium, Oulu, 2004.

Abstract : In this paper we propose the use of smart antennas in mobile relays as a way of achieving very high data rates over wide areas. We introduce a novel air interface concept and make an analysis of the cost of multi-antenna transceiver for the application relative the cost of single-antenna transceivers for existing standards.

- P Zetterberg and B Ottersten. "The Spectrum Efficiency of a Base Station Antenna Array System for Spatially Selective Transmission". IEEE Transactions on Vehicular Technology, vol. 44, no 3, Aug, 1995, pp. 651-660.

Abstract : In this paper we investigate the spectrum efficiency gain using transmitting antenna arrays at the base stations of a mobile cellular network. The proposed system estimates the angular positions of the mobiles from the received data, and allows multiple mobiles to be allocated to the same channel within a cell. This is possible by applying a transmit scheme which directs nulls against co-channel users within the cell. It is shown that multiple mobiles per cell is an efficient way of increasing capacity in comparison with reduced channel reuse distance and narrow beams (without directed nulls). The effect of the spatial spread angle of the locally scattered rays in the vicinity of the mobile is also investigated.

The following two references deal with the performance of beamforming based on measured data. These references show partner KTH experience in performance assessment on real data. Partner KTH have newer data than that used in the two last references above. The data is unique in some aspects, e.g. we have simultaneous measurements from two-sites enabling system-level evaluation on measurement data. This data and the techniques used to evaluate the data could be used to assess the performance of some of the techniques developed within Task 1-4, on issues such as channel estimation, adaptive modulation and antenna selection.

- P Zetterberg. "Performance of Three, Six, Nine and Twelve Sector Sites in CDMA - Based on Measurements". In Proceedings of IEEE International Symposium on Spread Spectrum Techniques and Applications. Aug, 2004.

Abstract : In this paper we investigate the performance improvement achieved by increasing the number of sectors on a W-CDMA or CDMA2000 site by increasing the number of sectors from today's typical three to six, nine or twelve. The radio propagation environment determines if the narrow beams can be created and kept separated or if they blur together, which in turn determines the sector-to-sector isolation and the soft-handoff populations. The rate of change in signal strength of the beams also determines whether the handover mechanisms are sufficiently fast to allocate the correct beam. In this paper we analyze these issues based on simultaneous measurements of two antenna panels placed on the top of a building overlooking a typical European urban environment of mostly six to eight stories high buildings. Based on these measurements and simulations we find that a nine-sector site has more than double the capacity of a conventional three sector site.

- P Zetterberg. "Performance of Narrow Beams in a Suburban Environment", In Proceedings of IEEE Vehicular Technology Conference (VTC 2000-Spring). Tokyo, May, 2000, 1235-1239.

Abstract : Based on measurement results, an analysis of antenna gain and side-lobe levels in a realistic propagation environment is performed. In particular, emphasis is put on the array gain as a function of antenna height and excess path-loss. Other parameters such as path-loss slope and shadow fading are also estimated. The implications of the extracted models and parameters on capacity and coverage of a cellular system are obtained through simulation. The analysis indicates that the lower antenna height yields higher capacity since its path-loss slope is higher, even though the directivity of the effective antenna patterns is lower. The coverage area of the higher antenna height is much larger than that of the lower. It should also be noted that basically no tilting is performed.

The last two references show some of the results obtained from partner KTHs test-bed (MUMS) which is also described in Section 2.1 of this document. The first one experimentally evaluates the performance of beam-forming in a scenario where ADC errors have been deliberately added to investigate their influence. The second gives and introduction to the test-bed, and also shows preliminary results of an implementation of spatial-mutliplexing (combined with adaptive modulation) with receiver-to-transmitter feedback and results from an implementation with interference rejection at the transmitter and the receiver.

- Henrik Lundin, Patrick Svedman, Xi Zhang, Mikael Skoglund Peter Händel and Per Zetterberg. "ADC Imperfections in Multiple Antenna Wireless Systems---An Experimental Study", 9th International Workshop on ADC Modelling and Testing, September 2004.

Abstract : This paper investigates some of the effects that ADC imperfections may have on wireless communication systems. First, an experimental communication system for wireless multiple-input multiple-output (MIMO) is described. In this test bed, an ADC behavioural model has been implemented. The resulting performance of the communication system, in terms of bit error rate, is assessed when the parameters of the ADC model are altered. The results show that, for this system, the ADC resolution is the key parameter while the non-linearity errors are of minor importance.

- P Zetterberg, J Jalden, H Lundin, D Samuelsson, P Svedman and X Zhang. "Implementation of SM and RxTxIR on a DSP-Based Test-Bed". The European DSP Education and Research Symposium (EDERS). November 2004. Birmingham, Great Britain.

Abstract: In this paper we describe the implementation of two smart-antenna strategies and associated signal processing algorithms on a common DSP-based wireless MIMO test-bed. The test-bed supports single-cell and two-cell configurations. All nodes (MS and BS) have two antennas (either two transmit or two receive) and there are feedback links (via cable) from the receivers to all transmitters. These possibilities have been utilized differently in the two techniques: spatial multiplexing (SM) and joint receiver transmitter and interference rejection (RxTxIR). The SM technique targets a single-link low-mobility scenario and boosts throughput using two parallel spatially multiplexed modulation streams. The RxTxIR scheme utilizes the two-cell configuration of the test-bed to demonstrate the possibility of suppressing inter-cell interference in transmitter as well as the receiver beamforming.

The following references represent **University of Piraeus Research Centre** (UPRC) know-how related to Reconfigurable/Adaptive Transmission Schemes, which work was performed under the umbrella of Cadence Design Systems in the R&D Department of Signal Processing Worksystem (SPW), with activities involving modelling, simulation, and performance evaluation of 3G wireless systems. The outcome of the work can be found in the SPW CDMA2000/3GPP2 library as a sample of the extensive expertise on simulation techniques for 3G wireless systems using SPW.

- G. Efthymoglou, and H. Helmken "Acquisition Performance of a Digital IF Receiver in a LEO Satellite Channel," Proceedings IMSC' 97, Los Angeles, California, pp. 65-69.

Abstract: A hardware real-time LEO acquisition system was simulated and tested in the laboratory. A technique known as Direct Coherent Detection (DCD) is used to recover the I & Q samples with the use of a single A/D. The acquisition performance of the IF digital receiver designed to account for the Doppler shift in the received signal from a LEO/MEO satellite channel is determined. The selection of receiver design parameters is based on real time signals and signal acquisition and subsequent processing via SPW software.

- S. Ghassemzadeh, G. Efthymoglou, Kourosh Parsa, and Joe Boccuzzi, "On the Performance of Multi-Code CDMA Systems: A Simulation," IEEE Sarnoff Symposium on Advances in Wired and Wireless Communication, March 17, 1999, Trenton, NJ.

Abstract: This paper describes the results of a comparison study of multi-code CDMA cellular systems under ITU channel conditions. The comparison study is simulation based and it is intended to evaluate the performance of multi-code DS-CDMA systems in a multipath environment.

The following references represent UPRC know-how related to the joint research activity on jointly optimised MIMO transceivers,

- Panagiotis D. Karamalis, Nikolaos Skentos, Athanasios G. Kanatas, "Selecting Array Configurations for MIMO Systems: An Evolutionary Computation Approach", Accepted for publication at IEEE Trans. On Wireless Communications.

Abstract: This paper presents an antenna selection method for Multiple-Input Multiple-Output (MIMO) wireless systems. By exploitation of the channel transfer matrix, the antenna selection criterion is the maximization of the instantaneous capacity achieved using a specific number of transmitting and receiving antenna array elements. For each environment, the proposed method applies a Genetic Algorithm (GA) which seeks the most advantageous subset of antenna elements. The results are based on measured and simulated channels and show that the proposed method selects array configurations that yield superior performance compared to conventional arrays. Furthermore, comparative analysis results are presented, with respect to a state-of-the-art algorithm.

- P. D. Karamalis, N. Skentos, A. G. Kanatas, P. Constantinou., "Comparison of existing MIMO antenna selection algorithms with an evolutionary approach", Presented at COST 273, TD(04)55 Athens, Greece, 2004/January/26-27.

Abstract: In this document, a GA-based MIMO antenna selection technique, initially described in TD-03-110, is compared with existing selection algorithms proposed by Gorokhov et al. and an exhaustive search method. Comparisons are performed on both simulated i.i.d and realistic measured channels. Results show the relative advantages and disadvantages of the algorithms in terms of their capacity performance and complexity.

- P. D. Karamalis, N. Skentos,A.G. Kanatas, "Adaptive Antenna Subarray Formation for MIMO Systems", Submitted for publication in Trans. On Wireless Communications

Abstract: MIMO systems with reduced hardware complexity have attracted researchers' attention due to their high efficiency and low cost. Sub-optimum algorithms for antenna subset selection have been intensively studied in the literature. In this paper we present a new technique to maximize the capacity of multiple antenna wireless systems with reduced available RF chains. The technique is based on the adaptive formation of subarrays, i.e. grouping antenna elements and applying appropriate element weights. The elements of each subarray and their weights are dynamically selected by an evolutionary optimization technique using the link capacity as a cost function.

- N. Skentos, A.G. Kanatas, G. Pantos, P. Constantinou, "Capacity Results from Short Range Fixed MIMO Measurements at 5.2GHz in Urban Propagation Environment", Presented at ICC'2004, Paris, 20-24 June, 2004.

Abstract: In this paper, wideband MIMO channel measurements conducted in Athens, Greece are described. Short range scenarios with fixed transmitter and receiver, in urban like environments under LOS propagation conditions have been measured, using an 8×8 vector channel sounder operating at 5.2 GHz. Based on the measured MIMO channel matrices, results of mean and outage normalized capacity calculations are presented. These results correspond to systems with various numbers of antenna elements and various ULA antenna configurations.

- N. Skentos, P. Constantinou, A. G. Kanatas, "Channel Characterization Results from Fixed Outdoor MIMO Measurements", Presented at WPMC'2004, Padova, Italy, 12-15 September, 2004.

Abstract: In this paper, channel characterization results from fixed, short range, wideband MIMO measurements are presented. Rooftop to street scenarios have been measured, under pure LoS propagation conditions, in an urban environment at 5.2 GHz. The characterization results reported herein, refer to the delay and Doppler dispersion characteristics, coherence measures and spatial fading correlation. Also the error induced by the frequently used Kronecker product assumption is evaluated for different MIMO systems.

The scientific know-how of **Instituto de Telecomunicações (IT)** focuses on the topics addressed in the following papers.

The first paper shows that the use of CSI at the BS may contribute to the goal of improving the performance as compare to MUD techniques and allow to transfer the computational burden from the MS to the BS. This was applied for the specific case of frequency domain MC-CDMA signalling with multiple antennas at the BS.

- Silva and A. Gameiro, "Downlink Space-Frequency Pre-Equalization Techniques for TDD MC-CDMA Mobile Radio Systems", to be published in an Eurasip journal.

Abstract: The paper considers downlink space-frequency pre-equalizations techniques for time division duplex MC-CDMA. We consider the use of antenna arrays at the base station (BS) and analytically derive different pre-equalization schemes for two different receiver configurations at the mobile terminal: a simple de-spread receiver without channel equalization and an EGC conventional receiver. We show that the space-frequency pre-equalization approach proposed allow to format the transmitted signals so that the multiple access interference at mobile terminals is reduced allowing to transfer the most computational complexity from mobile terminal to the base station. Simulations results are carried out to demonstrate the effectiveness of the proposed pre-filtering schemes.

Channel estimation for the uplink is a key challenge in MC-CDMA. The next paper deals with techniques that combines low complexity with reasonable performance. The application in this paper was still SISO.

- P. Marques and A. Gameiro, "Low-complexity Channel Estimation for Beyond 3G Systems" , VTC Fall, Los Angeles, sept. 2004.

Abstract: A Robust Minimum Mean Squared Error (RMMSE) channel estimation algorithm that does not rely on a priori knowledge of the channel statistics gives good results with MC-CDMA systems. The RMMSE estimator takes advantages of the correlation between all Np pilot-subcarriers and requires one Np by Np matrix inversion per each pilot symbol of the burst structure. This complexity can be large depending on the number of pilots subcarriers in the system. This paper presents and analyses two low-complexity suboptimal approximations of the RMMSE channel estimator. A complexity versus performance comparison is done. The performance is presented in terms of Mean Square Error for a 1024 tone MC-CDMA system over ETSI BRAN mobile channel models.

The next paper considers the specific case of UMTS-TDD signalling, and proposes techniques for performance improvements, through the use of multiple antennas and MUD. The techniques for MUD rely on a frequency domain approach, which leads to a lower complexity than the equivalent time-domain approach, and allow a uniform treatment with OFDM based signalling techniques, thus allowing the reuse of components in a multiservice system.

- L. Gonçalves and A. Gameiro, « Multi-Sensor Frequency Domain Multiple Access Interference Canceller for DS-CDMA Systems », Publication: ISSSTA, Sydney, Sept. 2004.

Abstract: Direct Sequence Spread Spectrum (DS-SS) signals exhibit cyclostationary properties which imply a redundancy between frequency components separated by multiples of the symbol rate. In this paper a Multiple Access Interference Canceller (Frequency Shift Canceller) that explores this property and applies to UMTS-TDD is presented. This linear frequency domain canceller operates on the spreaded signal in such way that the interference and noise at its output is minimized (Minimum Mean Squared Error Criterium). The Frequency Shift Canceller (FSC) is implemented in six uplink UMTS-TDD multiantenna configurations, three with reception beamforming and three with spatial diversity. Also three single antenna configurations are evaluated. All these configurations are evaluated concatenated with a parallel interference canceller (PIC). The results are benchmarked against the performance of the conventional RAKE-2D detector, the conventional PIC-2D detector and single user scenario.

The next paper represents an extension to MIMO of part of the work referred in the second paper.

- P. Marques and A. Gameiro, "Uplink MIMO channel estimation for beyond 3G systems", 3G2004 London, Oct. 2004.

Abstract: Multiple input multiple output antennas (MIMO) can be used in B3G systems to improve communication quality and capacity. The receiver should know the MIMO channel to achieve coherent signal detection. In this paper, we propose an efficient channel estimation technique for MC-CDMA systems and MIMO uplink transmission. The proposed MIMO channel estimator results of a simple extension of SISO channel estimator for each receiver antenna. The SISO channel estimator adopted is the robust minimum mean-squared error (MMSE) that does not require a priori knowledge of the channel statistics. The performance of the proposed MIMO channel estimation algorithm is demonstrated by computer simulation for B3G typical scenarios.

The last paper complements the results of the first reference work, by considering the sensitivity the CSI errors in the space-frequency pre-equalization technique. This allows to set bounds on the maximum velocity allowable for a given TDD frame structure or on the channel estimation tolerable errors.

- Silva and A. Gameiro, "Sensitivity Evaluation of Downlink TDD Space-Frequency Pre-Equalization Scheme for MC-CDMA Systems",

Abstract: This paper presents a downlink space-frequency pre-equalization technique for time division duplex MC-CDMA. We consider the use of antenna arrays at the base station (BS) and a single antenna at the mobile terminal. We show that the space-frequency pre-equalization approach proposed allow to format the transmitted signals so that the multiple access interference at mobile terminals is reduced allowing to transfer the most computational complexity from mobile terminal (MT) to the base station. One important issue for all pre-filtering schemes is that their effectiveness relies on the accuracy of the uplink channel estimates in modeling the downlink channel. Therefore, we evaluate the performance of both schemes in scenarios where the channel changes between an uplink and downlink slot, in order to obtain the performance penalties as a function of the time separation between the uplink (UL) and downlink (DL) slots.

We evaluated the performance of the algorithm in scenarios where channels between antenna elements are correlated.

The expertise of **Centre Tecnològic de Telecomunicacions de Catalunya** (CTTC) within this workpackage concentrates on four different aspects: design and optimization of MIMO transceivers with partial channel state information, analysis and performance evaluation of different beamforming architectures for present and future mobile communication systems, design of punctured space-time turbo trellis codes, and MIMO architectures of soft interference mitigation. The following are the most recent and representative publications in these areas:

- M. Navarro, A. Graell i Amat, Punctured Space Time Turbo Trellis Codes: Rate Adaptation and Optimisation Issues, IEEE Wireless Communications and Networking Conference (WCNC 2004). Atlanta (USA), March 21-25 2004.

Abstract: In this paper the use of puncturing under the scope of space time turbo trellis codes is considered. On one hand we consider the use of puncturing as a simple mechanism to allow varying the transmission rate, investigating the performance improvement/degradation when decreasing/increasing the spectral efficiency of the code. Then, we focus on the application of the EXIT chart technique to analyse the effect of puncturing on the code performance, and propose guidelines for the design of most suitable puncturing schemes.

- S. Pfletschinger, M. Navarro, A Low-Complexity MIMO System with Soft Interference Mitigation, IEEE Global Telecommunications Conference (Globecom 2004). Dallas (USA), 29 November - 3 December 2004.

Abstract: In this paper, we present a low-complexity combination of a BLAST-like MIMO system and bit-interleaved coded modulation with iterative decoding (BICM-ID). We present a method to exploit soft information stemming from the outer decoder to mitigate the influence of multistream interference. Furthermore, we introduce an inner code to remove the error floor which is normally present in BICM-ID systems. This code is of rate one and has memory one; it thus adds no redundancy and only very little complexity. Both schemes are evaluated in the EXIT chart and with BER simulations.

- Payaró, X. Mestre, M. A. Lagunas, "Optimum transmit architecture of a MIMO system under modulus channel knowledge at the transmitter", IEEE Information Theory Workshop (ITW 2004). San Antonio (USA), October 24-29 2004.

Abstract: In this paper, we study the ergodic capacity of a multiple input multiple output (MIMO) uncorrelated flat fading channel with perfect channel state information at the receiver and partial channel state information at the transmitter. We focus our attention on the case where the transmitter is informed only with the modulus of the channel matrix coefficients. First, we prove that a simple power allocation strategy among transmitting antennas is the optimal scheme, in the sense that is a capacity achieving architecture. Next, for the particular case where only two antennas are used at each communication end, we derive closed form expressions for the ergodic capacity and the optimal power assigned to each antenna.

- F. Rubio and X. Mestre, "Asymptotic performance of code-reference spatial filters for multi-code DS-CDMA", submitted at IEEE ICASSP 2005 (Special session on random matrix theory).

Abstract: We address the problem of code-reference spatial filtering for multicode DS/CDMA. The large-system analysis of the asymptotic performance of three spatial filters, respectively based on the matched filter, the decorrelator and a projector onto the span of the codes of the desired user, is presented. We derive analytical expressions for the asymptotic covariance and output signal-to-interference-plus-noise ratio (SINR) of these filters, assuming that both the spreading factor and the number of parallel code sequences increase without bound at the same rate. A superior performance of the projecting filter against the other two solutions is revealed: the performance of the spatial filters based on the matched filter and the decorrelator saturates both for increasing values of the input signal-to-noise ratio (SNR), whereas the projecting solution is able to sustain an increasingly high SINR.

- X. Mestre, M.A. Lagunas, "Diagonal Loading for Finite Sample Size Beamforming: an Asymptotic Approach", Chapter 8 of "Robust Adaptive Beamforming", J. Li and P. Stoica Editors, John Wiley and Sons, 2005.

Abstract: Minimum variance beamformers are usually complemented with diagonal loading techniques in order to provide robustness against several impairments such as imprecise knowledge of the steering vector or finite sample size effects. In this paper, we concentrate on this last application of diagonal loading techniques, i.e. we assume that the steering vector is perfectly known, and that diagonal loading is used to alleviate the finite sample size impairments. Our analysis is asymptotic in the sense that we assume that both the number of antennas and the number of samples are high but have the same order of magnitude. Borrowing some results of random matrix theory, we first derive a deterministic expression that describes the asymptotic signal to noise plus interference ratio (SINR) at the output of the diagonally loaded beamformer. Then, making use of the statistical theory of large observations (also known as general statistical analysis or G-analysis), we derive an estimator of the optimum loading factor that is consistent when both the number of antennas and the sample size increase without bound at the same rate. Thanks to that, the estimator has an excellent performance even in situations where the quotient between the number of observations is low relative to the number of elements of the array.

The scientific know-how of **Groupe des Écoles des Télécommunications (GET)** is described by references [72][73][74][75][76][77] and [90][91][92][93]. For the transmitter side, we knew how to design some 2 and 3 antennas full-rate codes. For the receiver side, we knew how to ML decode linear dispersion codes based on QAM constellations (whatever the spectral efficiency of the QAM can be). Moreover, we knew how to construct efficient non coherent space-time codes when neither the receiver nor the transmitter know the channel.

Based on the review of the state of the art and the reported know-how the following knowledge gaps were identified and an action plan was established to conduct future research and identify potential collaborations. They are structured around the following research tasks:

Advanced receiver structures:

- KTH identified the need for a practical transmission scheme that unifies the multiplexing scheme with the diversity scheme. It should utilize the partial CSI to trade off multiplexing with diversity but also adapt bit and power load so that the data rate is maximized given an approximate BER constraint and at an average power constraint.

  Some of the techniques on task 2 and 4 has not been evaluated on real-data, in particular in cases where there are more than one base-station, and not in all environments. Elaborate propagation models may also have missed important mechanisms that may influence the performance of some particular techniques.

Some of the techniques and antennas of task 2 and 5 have not been made operational in a real-time test-bed. In a real-time test-bed implementation aspects are discovered that may have been overlooked in the analysis.

- CTTC identified a knowledge gap regarding the study and theoretical characterisation of iterative multi-antenna schemes incorporating semi-blind channel estimation and symbol detection; with application to DS-CDMA MC-CDMA
- IT interests lie in channel estimation techniques for MC-CDMA, focusing on uplink transmission with multiple antennas at the BS, and space-frequency pre-equalization for MC-CDMA and DS-CDMA at the BS.
- UPRC research interest concerns the channel estimation module at the receiver, which accuracy, complexity and performance is critical for the signal recovery and the re-configurability issues at the receiver side. The work involve identifying the target mobile radio propagation channels as well as the schemes (e.g. multi-carrier architectures) under which the various channel estimation techniques are going to be evaluated. The existing algorithms/architectures are going to be evaluated in both classic model and realistic propagation channels. The outcome of such a process target not just to classify the various channel estimation procedures, but also to identify the significance of the estimation accuracy in a re-configurable system. Furthermore, reduced complexity estimation is going to be addressed in order to evaluate the overall performance degradation. Extensive investigation is going to be performed on the shortcomings of the considered algorithms with key points on the decisions thresholds of the training/decision directed modes, of the semi-blind possibility and of the re-configurability according to the environment characteristics.

Reconfigurable/Adaptive Transmission Schemes:

- CTTC finds further work is of interest regarding the analysis of capacity-achieving MIMO architectures for partial channel state information at the transmitter and development of scalable approaches, so that an optimum transmission strategy is selected according to the available CSI. Design of algorithms that optimize resources depending on channel conditions and training sequence length as well as implementation issues related to the deployment of smart antennas in future wireless systems are to be investigated.
- KTH has identified that the performance of smart antenna and MIMO schemes are often highly dependent on the propagation environment. The schemes are often derived under assumptions regarding the channel that may or may not does not hold in practice. It is therefore highly advantageous to be able to test the schemes using long traces of channel measurements. This applies in particular to transmit beam-forming where the gain is either obtained from either a spatial stability of the channel (which enables directional beam-forming gains) or temporal stability (which enables the use of old estimates of the channel). The propagation is extremely critical when it comes transmit beam-forming with interference rejection at the transmitter as outlined in Section 0. The project identified a knowledge gap with respect to the availability of channel measurements and evaluation of performance based on those measurements. To address this gap measurement campaigns have been performed (as detailed in the following sections) and data used for realistic performance evaluations,
  - Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance
  - Interference Rejection at the transmitter and associated feedback

Real-time implementations are also useful in assessing the complexity of approaches and forcing the researchers to address every aspect of the design such as synchronization, frequency tracking etcetera that is often overlooked. Such issues have been addressed in the implementations in Section 2.2.1. Two implementations have been finalized during the first phase of ACE namely a "Spatially Multiplexed MIMO System" and "Smart Antenna Multiuser Algorithm". The first addresses techniques such as outlined in Section 1.3.1 while second correspond to the schemes of Section 1.3.2.

Techniques for interference rejection in the transmitter and the feedback has not been developed and analysed for data-centric applications and therefore their performance is unknown. The largest gains can be expected in slowly varying channels.

- UPRC interest on adaptive transmission schemes are on the development of logic schemes based on specific receiver measurements/requirements (channel estimation, SIR estimation, FER) that will feedback to the transmitter the modulation/coding format to be used. Investigation of the effect of feedback delay on system performance, in different channel environments is considered an open issue.
- IT is looking at schemes that combine space-time coding with pre-equalization. In particular, robust pre-equalization schemes (adaptive schemes that can use partial or full CSI according to the reliability of the parameters) with special emphasis on the comparison of capacity aspects when using spread versus orthogonal signalling schemes for cellular communications. Of interest is also differential transmission techniques to minimize the overhead associated with pilots / training sequences, that are required for MIMO channel estimation. And the last subject, closely related to WP2.2-4 activity, deals with joint scheduling and adaptive link selection for multiple antenna transmitters.

Jointly Optimised MIMO Transceivers:

- UPRC identified open research problems in the area of antenna selection algorithms. The performance evaluation of existing antenna selection algorithms under different channel conditions is an aspect that needs to be further examined. For this purpose, a number of different channel types shall be simulated and then used, in order to examine the performance and characteristics of existing antenna selection techniques.

  MIMO antenna subarray formation systems and algorithms is a new and promising field, which combines lower complexity and cost as well as enhanced system performance in terms of capacity. A key-point in antenna sub-array formation is the use of all available antenna elements, instead of a sub-set, exploiting both diversity and array gain and, hence, yielding enhanced capacity performance compared to a conventional antenna selection system.

  Comparison of alternative criteria used for antenna selection is a gap that may serve as the basis for extensive research integration within ACE. Since UPRC and ICCS do cooperate in the previously mentioned points, there exists the possibility for further integration with CTTC. The antenna selection schemes could be the common basis of cooperation in terms of cross-layer optimization that fits also in WP2.2.4. An extensive discussion is required in order to form specific scenarios to be implemented.

2.2 Existing prototypes

The initial know-how on test-beds and prototypes is represented in the network by two organizations: the MIMO test-bed of Polytechnical University of Madrid (UPM) and the MIMO test-bed of the Royal Institute of Technology (KTH). The prototypes are introduced next, followed by a description of the upgrades, new developments and implementations that have taken place during the course of ACE activity in the last two years.

In the area of implementation of MIMO systems, research focus on different technologies. Several research groups focus their effort on implementation of MIMO schemes for OFDM-based systems, such as WLAN.

For instance, we find the Communication Systems Research Laboratory from Motorola Labs, lead by Frederich W. Vook, the Communication Theory Group from ETH Zürich [223], lead by Prof. H. Bölcskei, and the Smart Antenna Research Laboratory from Georgia Tech [219], lead by Prof. A. M. Ingram. Researchers from Georgia Tech have developed a smart antenna receiver with eight independent channels, which is being used to implement and test channel estimation and synchronization algorithms for MIMO systems, and MIMO channel measurements. We also find a 4×4 MIMO system compatible with WLAN 802.11a standard developed in Bristol University [220]. It uses TI C-6201 fixed-point DSPs for controlling the correct operation of the system, while the processing is performed in a host PC. The PC performs an off-line processing in order to analyze different coding/decoding schemes.

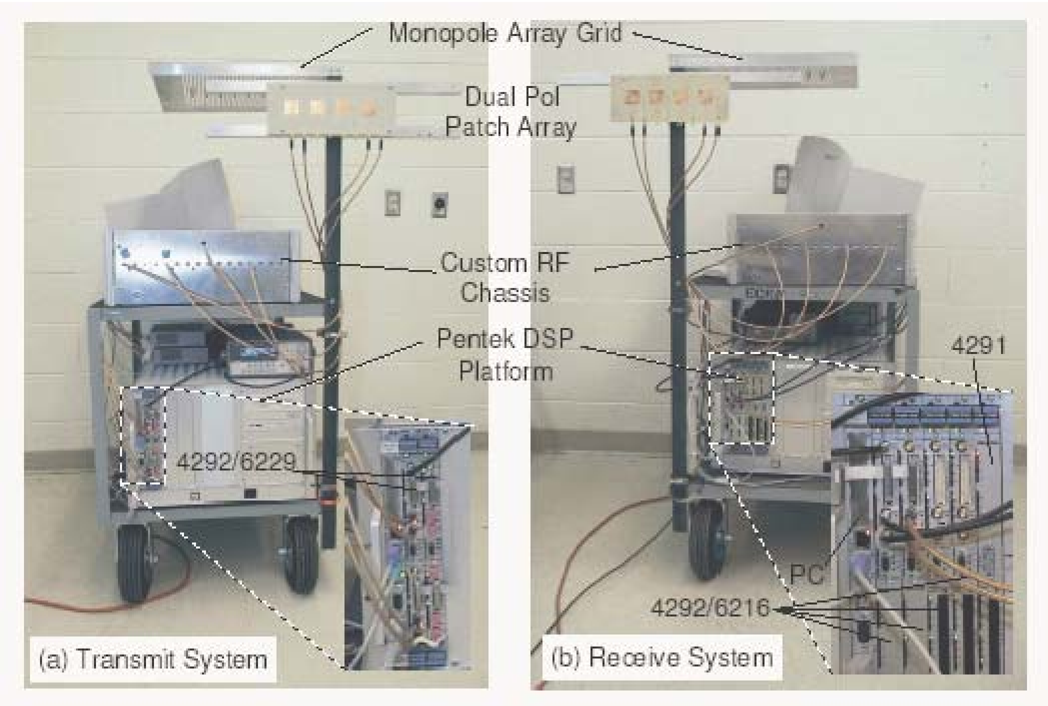


Figure 5. Photo of the transmit and receive subsystems [221].

In [221], a flexible architecture for a 4×4 MIMO system is presented (the prototype is scalable to 8 antenna elements). The test-bed has been developed to test different MIMO algorithms and their real-time performance. The architecture is implemented in a commercial Pentek platform, which uses wideband transmitters and receivers with sample rates over 65 MS/s. The DSP platform consists of cards with four fixed-point TI TMS320C6203 300 MHz DSP each. The platform provides high speed interfaces between different modules, allowing for scalability as not all DSP are used simultaneously. With a 4×4 MIMO system implemented in this platform, real-time video streaming can be offered with twice the resolution of a single element case (the transfer rates are 500 kbit/s and 2 Mbit/s, respectively), without increasing the transmit power, bandwidth and constellation size. Figure 5 (a) and (b) shows the transmit and receive chassis of the prototype, respectively.

Other interesting research lines focus on the investigation of real time architectures for MIMO systems. In this area it is interesting to highlight the activity at the Institute of High Frequency Technology from the RWTH Aachen University [227], lead by Prof. Dr.-Ing. Bernhard Rembold, and at the Smart Antenna Research Team from the University of Duisburg [222], lead by Prof. Prof. Dr. Andreas Czylwik. They make use of combined DSPs and FPGAs to provide flexible MIMO antenna architectures and to allow for meeting real-time requirements.

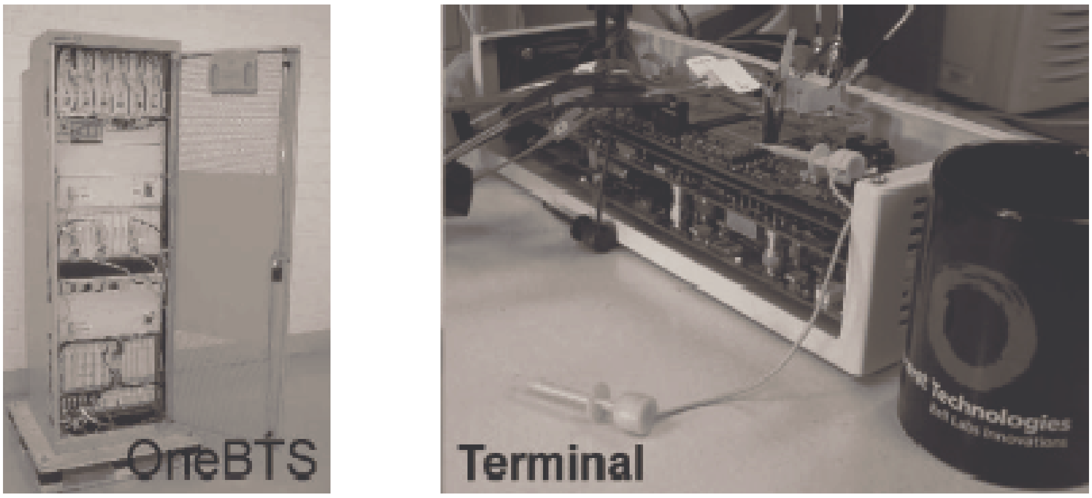
An 8×8 MIMO system for the ISM band (2.4 GHz) has been developed in the University of Bremen, within the Department of Communications Engineering [224]. This demonstrator, denoted as MASI (“Multiple Antenna System for ISM-Band Transmission”), makes the data processing offline in a workstation environment and it has been applied to blind source separation, to the study of block time codes and also to the evaluation of diversity transmission schemes. Figure 6 shows the transmitter and receiver platforms of MASI demonstrator.

(a) MASI transmitter

(b) MASI receiver

Figure 6. Photographs of MASI transmitter and receiver [224].

In [226], the integration of a MIMO prototype with a precommercial OneBTS basestation is presented. Both the transmitter and receiver architectures are implemented with DSPs and FPGAs. The 4×4 system is capable of achieving downlink raw data rates of 1 Mbit/s with a spreading factor of 32, following the specifications of UMTS (chip rate of 3.84 Mbit/s). With these capabilities, a video streaming application has been proved to work in real time. Figure 7 shows the basestation and prototype terminal.



(a) (b)

Figure 7. (a) Transmitter in OneBTS. (b) Prototype terminal [226].

There are also a good number of wideband MIMO channel sounders for different frequency bands [228]-[230]. A typical channel sounder architecture for MIMO is shown in Figure 8. These systems are very useful for the characterization of the MIMO channel properties, in both time and space domains (multidimensional joint channel parameter estimation). Different array geometries can be found, from the traditional linear or planar, to the spherical array [228], which provides a large angular resolution and range.

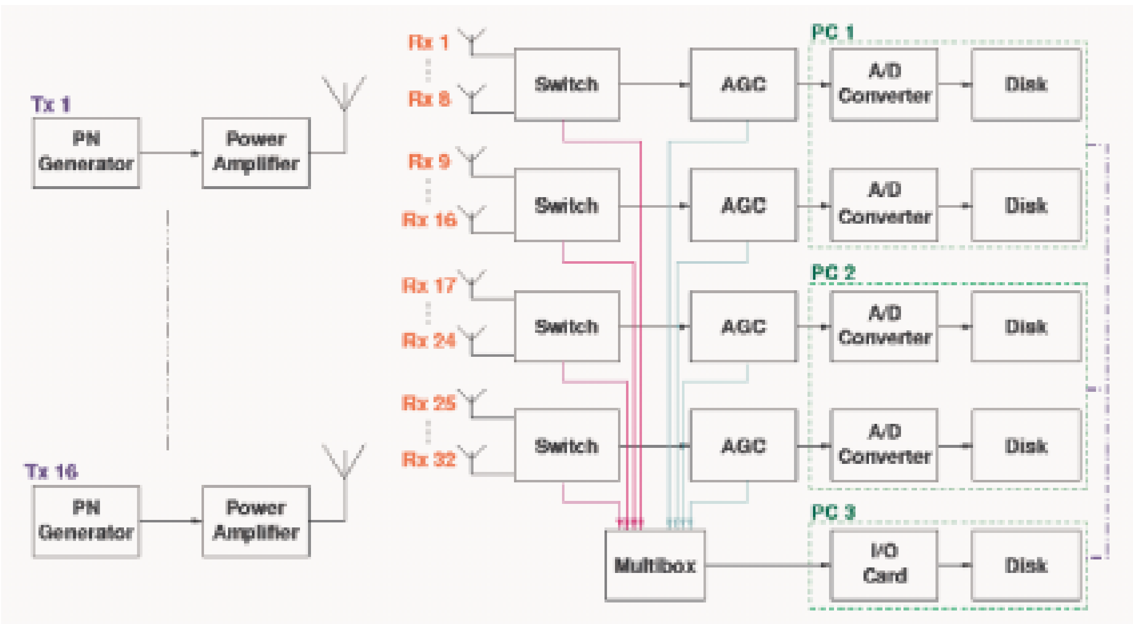
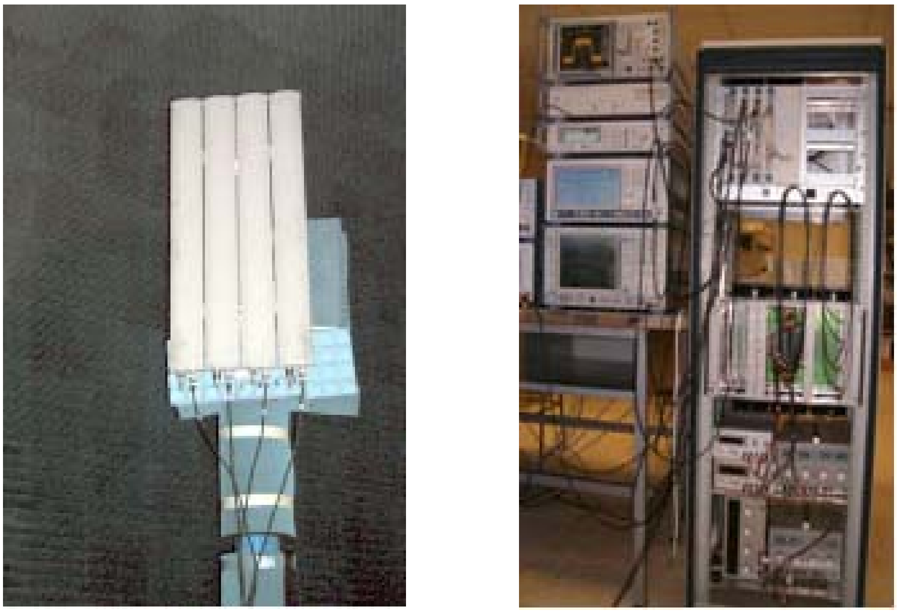


Figure 8. Architecture of a MIMO channel sounder [228].

Within ACE partners there have also been active work on the implementation arena. The Radiation Group from the Polytechnic University of Madrid, have finished a prototype of an adaptive antenna system (MISO) for W-CDMA [225], **ADAM**. Not only the prototype has been implemented, but also the definition of performance tests in canonical (anechoic chamber) and real scenarios have been specified.

As it can be seen in Figure 9 (a), the antenna array subsystem is formed by four commercial sectored antennas placed in a uniformly spaced linear geometry. The modem and beamforming subsystems (Figure 9 (b)) have been implemented using a Pentek platform, formed by wideband receivers, transmitters and quads with fixed-point TI TMS320C6202 250 MHz DSPs. The current implemented adaptive algorithm is the Normalized Least Mean Square (NLMS), due to its reduced computational complexity.

One of the main issues to investigate is related with the integration of the smart antenna with the existing infrastructure (i.e., base station). Not only dedicated channels are transmitted by the base station, but also control channels that must not be beamformed and should be received in all the cellular area. These channels usually transport cell, access and broadcast information. The developed MIMO prototype has to be able to interact with the system to decode the control transmitted signals correctly. A plug and play architecture has been developed that makes use of modified beamforming schemes in the uplink and downlink [53]. The main advantage of this system is that it is Node B manufacturer independent and does not require excessive deployment costs.



(a) Antenna array subsystem. (b) RF/IF and baseband subsystem.

Figure 9. ADAM prototype [225].

The **Multi-User MIMO Test System (MUMS)** is a test-bed which has been developed in the signal processing group at the Royal Institute of Technology (KTH). The test-bed consists of up to four radio nodes. Two of the nodes are transmitters (TX1, TX2) and two are receivers (RX1, RX2).

All nodes have two antennas (i.e. the entire setup has eight antennas), two transmitter or receiver modules, [50], one TI C6701 DSP processor and a host PC. There are feedback links from both receiver nodes to both transmitted nodes, implemented using a cable. The purpose of the platform is to enable researchers with a background in simulation and analysis of smart antenna systems to make real-time implementations of existing and novel MIMO schemes with an effort of a few man-months. Note that since there are four nodes, interference and multi-user aspects can also be studied. When working with the test-bed the researchers will gain insight into hardware, software and at the same time provide publishable experimental results.

To enable this, RF transmitter and receiver modules have been built with a transparent design that allows the graduate-students/researchers to understand and analyze them. Software skeletons that provide basic functionality such as buffer-handling, up- and down-conversion, filtering, and feedback have also been written, see [51]. This enables the researchers to concentrate on implementing the MIMO algorithms. Indeed, what there have to be implemented are two functions TX_Algorithm and RX_Algorithm which are then called by the real-time kernel of the skeleton. The function TX_Algorithm runs in the transmitter and has two inputs, one being the bits to be transmitted and the other the feedback information from the two receiving nodes. The output of TX_Algorithm is a buffer of complex-valued symbols which are then used by the skeleton functions to format a transmit burst which is sent to the D/A converter and is then up-converted and amplified by the analog radio transmitter hardware. The RX_Algorithm uses complex-valued samples from the receiver antennas, which have first been down-converted and amplified by the analog radio received hardware and then sampled, further down-converted and filtered by the skeleton software.

Using a common skeleton for several implementations also makes comparisons easier. Host PC software for demonstrations and algorithm comparisons have also been implemented. The software allows several algorithms to run in sequence in order to enable comparison of several schemes under comparable conditions. This is done so that each algorithm is run for 0.2 seconds, during which 67 radio frames are sent. Each frame consists of 32 symbols. It is the task of the researchers to define the format of these frames. The researchers also define the use of the feedback channel which sends 32 bits from each receiver node to both of the transmitter nodes in every frame. Due to delays in the system, the transmitter will not receive any feedback information before the fifth frame, i.e. it transmits the first four frames without any such information.

The symbol rate of the air-interface is only 9600 symbols per second. This is very small but has the advantage that very advanced real-time schemes can be implemented entirely in software. Since the transmit power of the system is only 0.2 mW (per antenna) the power per symbol is actually similar to wideband wireless systems. Under favourable conditions the system can deliver signal to interference ratios on the order of 40dB, which implies that very high signal constellation sizes can be used. Indeed, 64QAM has been successfully implemented and promising results have been seen from 256QAM. The test-bed has used 455.850 MHz carrier frequency until now. However, in this band there appear to be high levels of man-made noise generated by computers and therefore it will soon be reconfigured to 1766.600 MHz carrier frequency.

The test-bed is available for use in the ACE project, and can be used to demonstrate and compare methods developed within the project. As a side-effect, links will be established among the researchers and groups participating in the effort.

2.2.1 Upgrades, improvements achieved during ACE phase I

Within the framework of ACE the existing prototypes of UPM and KTH have seen a considerable improvement. The UPM test-bed has resulted in a new MIMO prototype. The work has concentrated on the development of the prototype itself, which upgrades and capabilities are described next in detailed. On the other hand the MUMs KTH test-bed has provided the framework for implementation of new algorithms, in particular the implementation of 2x2 MIMO system employing adaptive modulation and spatial multiplexing on the KTH MUMS test-bed has been performed as well as an implementation of a smart antenna multiuser algorithm with interference cancellation at the transmitter.

Taking the advantage of the gained experience in prototype implementation based on Software Define Radio (SDR) platforms achieved during the development of the ADAM prototype, a new prototype has been developed in the Radiation Group of UPM. First, the multiple antenna feature has been extended to the transmitter side resulting in a MIMO system, as compared with the SIMO ADAM prototype. A different operation radiofrequency has been considered for the new test-bed, since it was designed to be used for WLAN applications. Thus, the radiofrequency modules have been completely redesigned and implemented, using an RF frequency of 2.45 GHz. Also a different operation mode is considered for the MIMO test-bed, aiming at simplifying the algorithm testing: the signal pre and post processing takes place in an off-line basis instead of the real-time operation of ADAM. Thus, the tight real-implementation constrains when programming the MIMO algorithms to be tested are avoided. Nevertheless, some parts of transmission and reception are performed in real-time, such as filtering or up and downconversion. The same type of SDR platforms as the ones utilized in the ADAM prototype are used in the MIMO test-bed, namely several TI DSPs and FPGAs gathered in 2 QUAD boards. The digital up and downconversion is performed in the FPGAs, while the DSPs perform the signal reception and transmission, as well as the storage in memory. Next follows a detail description of each of the modules that form the test-bed with its current capabilities.

The UPM MIMO test-bed offers a number of features that make it especially suitable for research and educational purposes. A flexible architecture has been considered, by using a Software Radio implementation based on FPGAs and DSPs.

As an improvement on other existing prototypes, the proposed scheme considers the use of offline PC-based signal processing for both signal generation in transmission and demodulation processing in reception, thus allowing the user to easily design and implement his or her own algorithms, without the need of having to spend time in real-time implementation issues.

The algorithm analysis is simplified and the time needed to develop and test the possible MIMO schemes and methods under study is reduced. Finally, the antenna module has been designed to let the user change several physical features, such as the spacing between antennas and the type of radiating elements, which offers the possibility to study the effect of such parameters in the algorithm under test.

Figure 10 shows the hardware block diagram of the designed MIMO system, for the transmitter and the receiver respectively. It consists of a 4 x 4 MIMO channel, where a personal computer (PC) is used in each side of the link to perform control and offline processing. Each PC communicates with the digital signal processing boards.

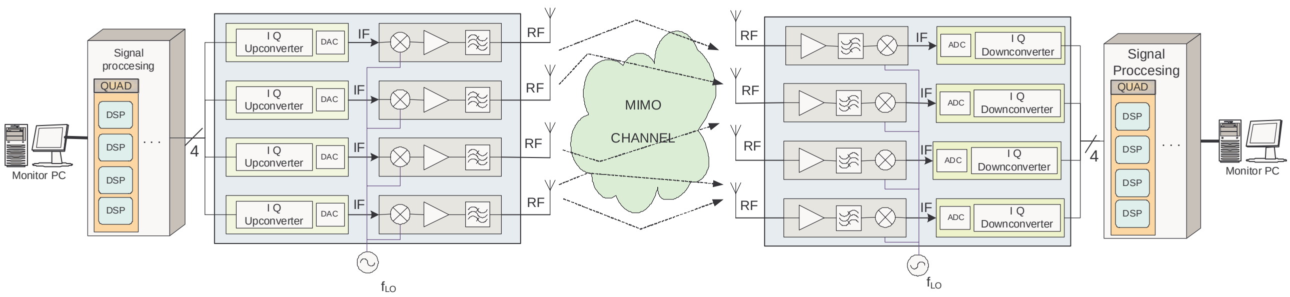


Figure 10. Transmitter architecture of the proposed MIMO system

The baseband signals are processed by digital upconverters and digital to analog converters (DACs), and the resulting analog signals are sent to the RF chains, built with commercial elements. After transmission over the MIMO channel, the opposite operation is performed in the receiver. The selected IF, 40 MHz, is digitally generated in the up and downconverters. The sampling frequency for digital to analog converters (DACs) and ADCs are derived from internal crystal oscillators. While ADCs sampling frequency is fixed to 100 MHz, DACs frequency can be chosen at multiples of 50 MHz (the internal oscillator), up to 200 MHz. Subsequent decimation and interpolation are done to adjust binary rate. The local oscillators are obtained from commercial signal generators, and their frequency are chosen to operate at RF frequency of 2.45 GHz (802.11 WLAN standard).

2.5.1.1 Signal processing module.

The signal processing modules may change from one application to another, but thanks to the SDR-based implementation the required updates are easily implemented. In the proposed MIMO test-bed, a basic transmitter-receiver scheme is considered, since we aim to obtain an architecture as general as possible. The software defined radio technology uses the commercial standard VME bus structure to host the processing boards (Figure 11). The four digital transmit chains are performed in a Pentek 4292 Quad DSP

(TMS320C6203) board and two Pentek 6229 digital upconverter daughter boards [18]. In the reception side, the four digital receiver chains consist of another Pentek 4292 Quad DSP (TMS320C6203) board and two 6235 digital downconverter daughter boards.


Figure 11. Software Defined Radio platform with 4292 Pentek boards

The modular scheme for digital processing is depicted in Figure 12. The basic transmitter consists of a source generator, a modulation mapping module and a pulse shaping. Additional pre-processing techniques and algorithms can be easily included. In the receiver, a matched filter is required, as well as an automatic gain control module.

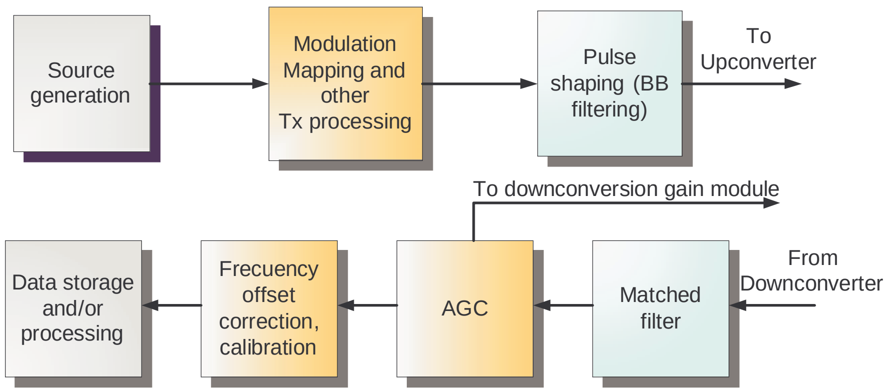


Figure 12. Digital modules.

The received signal is sampled by ADCs. This processing unit supports 12 bits in ADC and hence a high dynamic range. The sampling rate can be up to 100 Msamples/s. Figure 13 shows the upconverter and downconverter schemes.

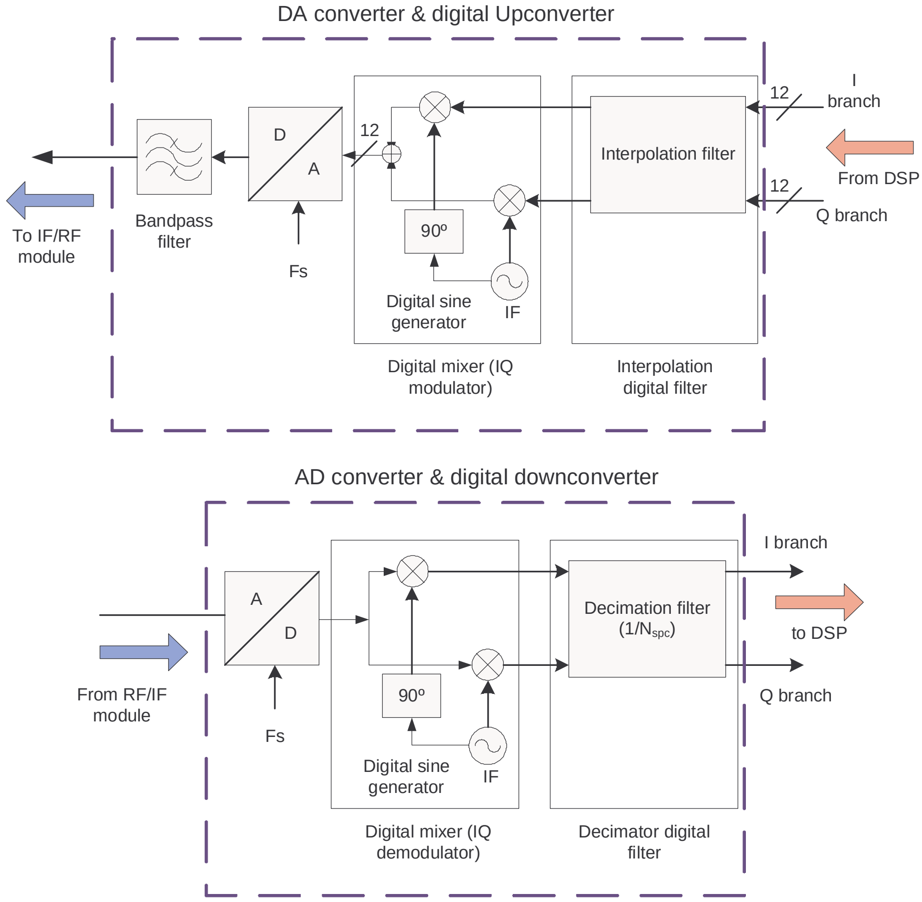


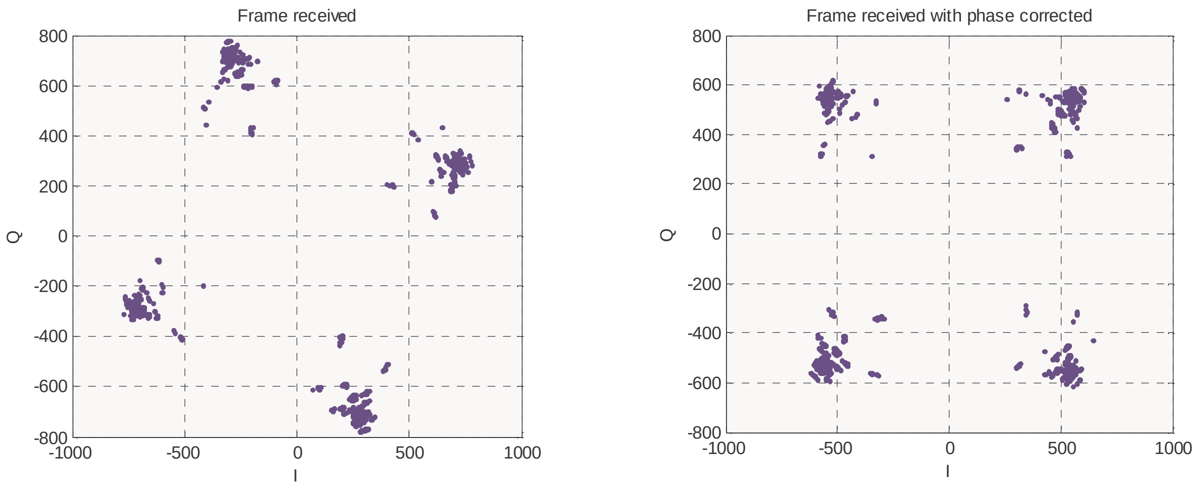
Figure 13. Digital Up and down converter schemes.

The received signal is converted to baseband by the digital downconverter, which outputs two branches (I and Q). Finally, the signals are filtered with a decimation filter, whose decimation rate can be selected by the user. With the current system memory, 320 ms of sampled signal can be stored for offline processing.

As RF oscillators are different in the transmitter and the receiver, a frequency offset estimation and correction is needed. The current test-bed implementation could be improved by considering other calibration aspects, in order to correct differences between chains, but this is left for future work.

A back-to-back calibration is carried out and a compensation matrix included. Finally, data storage and post-processing are performed. It should be notice that source generation and post-processing units are performed in the PC in an offline basis.

Figure 14.a) represents the constellation of a received frame of the transmitted signal. Figure 14..b) shows this constellation once the phase error has been corrected. This is realized thanks to a pseudonoise code of 256 bits sent by the transmitter.



a). Without correction **b). With phase corrected**

Figure 14. Constellation received

The signal processing can be carried out in different ways or operation modes. As a first mode, the system can work in an offline basis, where the source signal is generated and pre-processed, then transmitted through the MIMO channel and finally received and stored in memory, so that an offline processing can be realized in the PC.

Hence, only the up and downconverters, the DACs and ADCs and the RF modules operate in real time. This was the selected operation mode in the first version of the prototype system, for the sake of simplicity. It allows a straightforward testing of algorithms, avoiding real-time problems, and at the same time adding practical effects, since the real channel is included.

On the other hand, the communication between the FPGAs-DSPs modules and the PCs occurs by means of the specific libraries for the selected SDR platforms, which allow the communication with Matlab via TCP/IP protocol, as depicted in Figure 15.

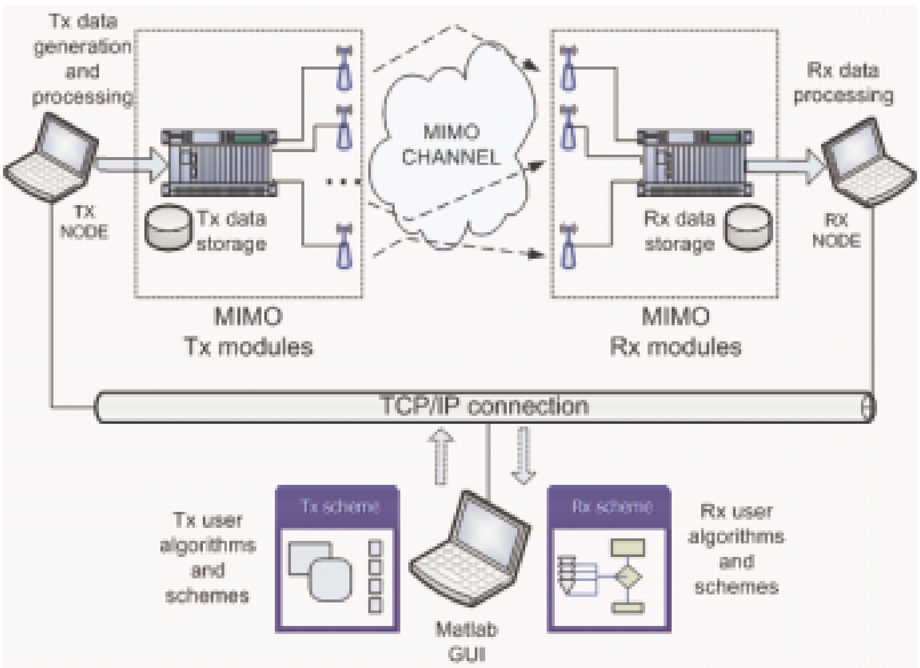


Figure 15. MIMO test-bed communication with PC.

The software development of the test-bed is based on Pentek Swiftnet environment, which supports remote access through TCP/IP connection. This is possible thanks to stream API of Swiftnet, which provides a means for moving streams of data between host and target in real-time. In our case, Matlab is the client application which is running in the host, hence a flexible performance is possible.

Thus, the implementation of a friendly user interface is straightforward. In order to work with a high data rate, real-time transference between DSP and PC is not suitable. Therefore, the received signal is stored in DSP memory and later sent to the Matlab application.

2.5.1.2 RF module.

The Radiofrequency module is based on a conventional heterodyne scheme in both transmitter and receiver chains. The selected intermediate frequency is 40 MHz, so the transmitter consists of a mixer in order to up convert frequency to RF at 2.45 GHz and three amplifiers.

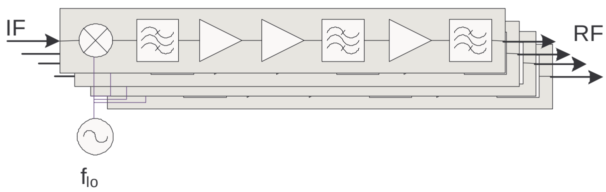


Figure 16. RF transmitter scheme.

Figure 16 shows the block diagram of the RF transmitter module. The local oscillator is generated and distributed to 4 chains through a 1 to 4 divider. In each chain, IF input signal is mixed, filtered and amplified by surface mount components. Figure 17 shows the scheme for RF receiver module.

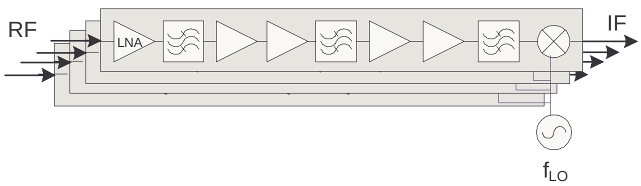


Figure 17. RF receiver scheme.

The low maximum transmitted power level (+10 dBm) restricts the MIMO test-bed to picocell environment purposes. Most of the RF components are low-cost and small-size ones. RF chains are mounted inside a metallic box in order to avoid coupling and isolate it of other chains or external interferences.

In reception, RF signal is received and amplified with the aim of increasing power level received in processing module, since the DSPs sensibility is around -40 dBm. Therefore, it is necessary to consider a low noise figure in the receiver scheme, which is achieved by using an LNA (Low Noise Amplifier). In Table 1 all components used in RF chains are detailed.

Table 1. Components of RF chains

Component	*Manufacturer*	*Description*	*Connector type*	*TX/RX*
ECG008	WJ Communications	Amplifier	Surface mount	Tx & Rx
ZX05-C42LH	Mini-Circuits	Mixer	SMA	Tx & Rx
855916	Sawtek	Filter	Surface mount	Tx & Rx
ZX10-4-27	Mini-Circuits	Divider	SMA	Tx & Rx
SMIQ	Rohde & Schwarz	Generator	N	Tx & Rx
ZX60-3011	Mini-Circuits	LNA	SMA	Rx

The implementation of the RF receiver chains are depicted in Figure 18, whereas Figure 19 and Figure 20 show the transmission parameter $|S_{21}|$ measurements of the four transmitter and receiver chains, respectively.

Figure 18. Implementation of RF chains.

In a similar way as in the transmitter, a local oscillator generates a tone which is sent to four chains through a 1 to 4 divider. Since the local oscillator is different in transmitter and receiver, frequency tracking in reception is required. Calibration is carried out in the transmitter and the receiver to know the differences between chains and mitigate their effects.

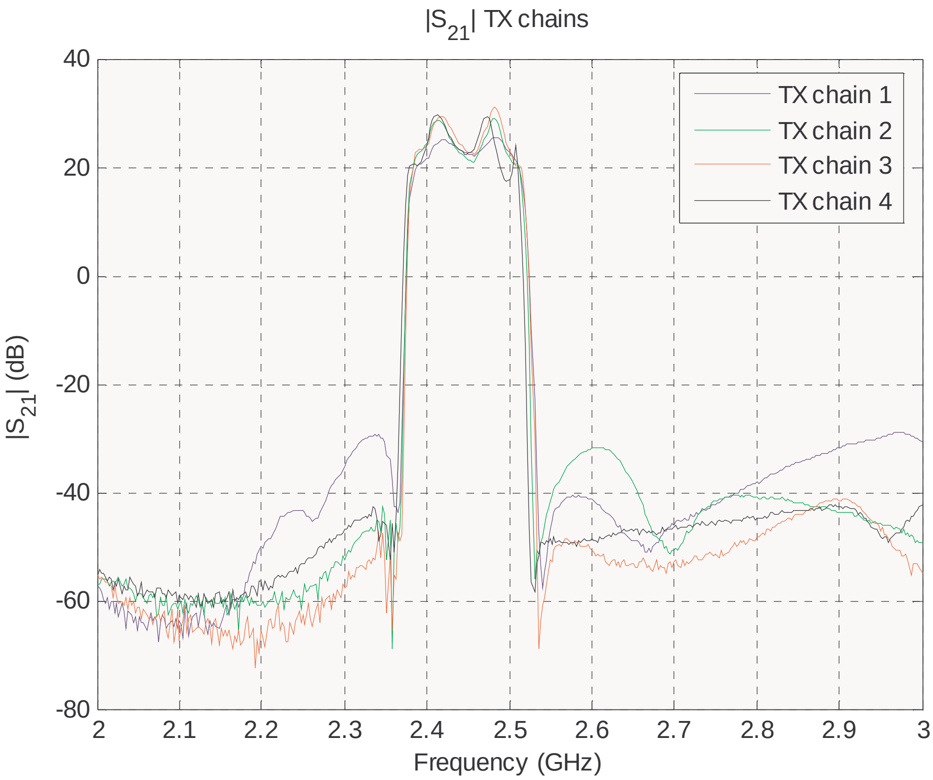


Figure 19. Measurements of the transmitter chains.

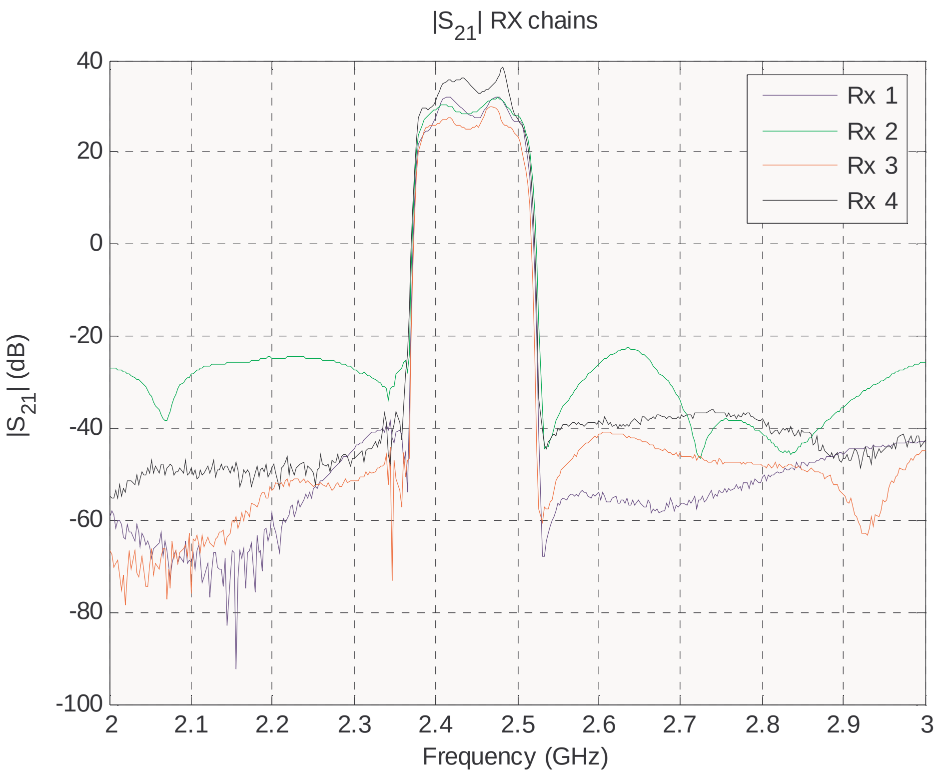


Figure 20. Measurements of the receiver chains.

2.5.1.3 Antenna module

The design of antenna module has been realized taking into account the possibility of using different array configurations. The radiant element is selected to be an omnidirectional one in order to obtain all possible multipaths. Thus, we chose λ/4 monopoles as radiating element for transmitter and receiver antennas.

The implemented antenna array module is shown in Figure 21, where four λ/4 monopoles working at 2.45 GHz are placed on a ground plane. Several configurations of antenna structure can be selected by varying the distance between elements. The minimum and maximum possible distances are 0.1 λ and λ, respectively.

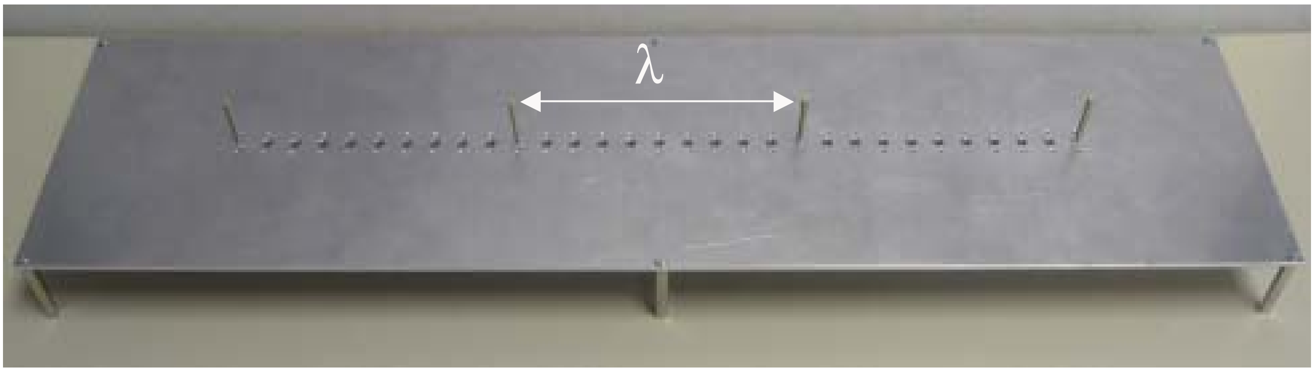


Figure 21. Implementation of the antenna module.

Omnidirectional elements (Figure 22) are used in this first antenna configuration in order to study multipath characteristics of the propagation channel. Regarding the antenna elements, other possibilities can be implemented in order to increase directivity, such as Yagi antennas.

Figure 22. Implementation of the monopole.

The radiation patterns of the monopoles are simulated using CST-Microwave Studio® in order to check the different gains which each radiating element offers with an element spacing of λ (12.25 mm for 2.45 GHz). Figure 23 shows antenna structure in the simulation.

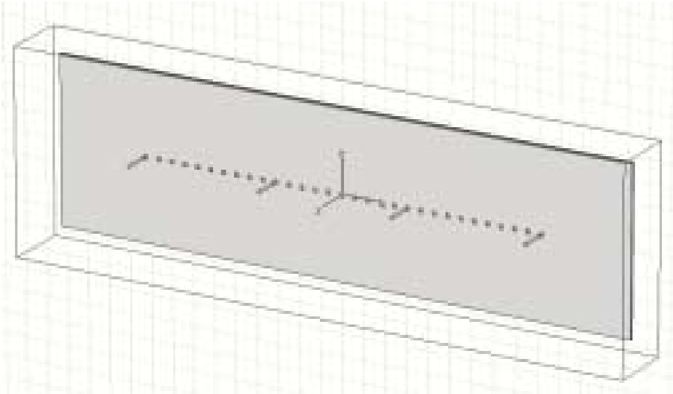
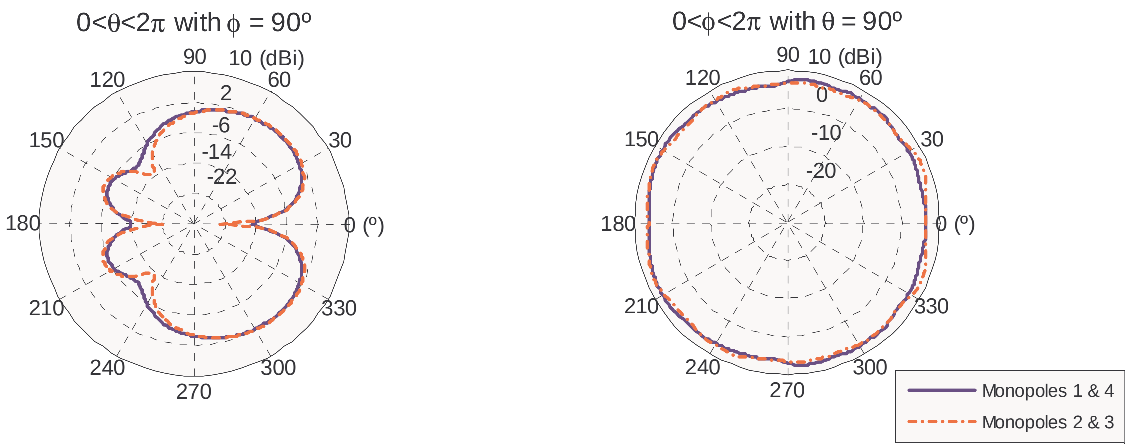


Figure 23. Simulated antenna structure.

The monopoles at the edge of the structure radiate with lower gain than the other ones, due to different ground plane conditions.

As Figure 24.a) and Figure 24.b) show, the radiation pattern is very similar in two monopoles which are separated λ.

Monopole number 1 is the first element on the left depicted in Figure 23. Similarly, monopole number 2 represents second element, and so on. As monopoles number 1 and 4 have the same radiation pattern and monopoles number 2 and 3 too, only monopoles number 1 and 2 are represented in the figures above. Direction of Φ=0º represents the axis where monopoles are situated and Φ=90º indicates perpendicular direction to ground plane.



a) Elevation **b) Azimut**

Figure 24. Radiation pattern

On the other hand, in order to study coupling effects between radiating elements, several measurements are performed. Figure 25 represents coupling coefficients regarding frequency and distance between monopoles.

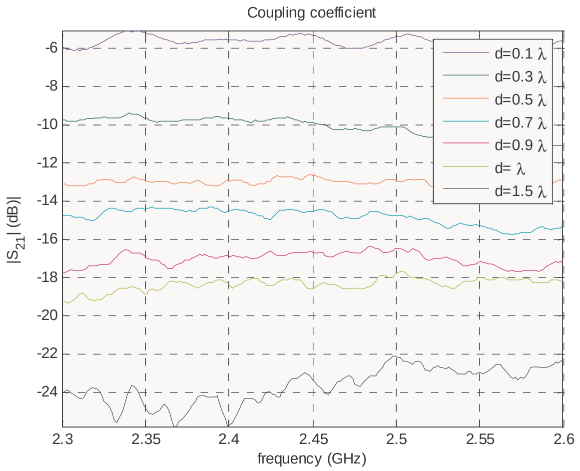


Figure 25. Measured coupling coefficients.

Several potential applications and use of the MIMO test-bed that have been identified of interest to this and other participating partners are outline next.

As a first application, the proposed MIMO test-bed can operate as a **channel sounder** (Figure 26). Channel measurements can be carried out in order to obtain the features of the specific scenario where the system will be used, in terms of capacity, spectral efficiency and channel correlation coefficients.

Figure 26. Main window of channel sounder application.

The second application focused on **educational purposes**, with the aim of making the understanding of communication theory easier for students by means of MIMO experiments. A flexible configuration is possible due to the operation mode of the test-bed, which is controlled by means of a highly flexible and user-friendly graphical interface (GUI) developed in Matlab environment.

A third application deals with **testing of MIMO algorithms**, with the intention of verifying space-time coding and different modulation schemes. Several configurations are possible regarding the number of antennas in transmission and reception. Thus, different $M \times N$ MIMO schemes can be established varying M and N between 1 and 4, where M denotes the number of transmit antennas and N the number of receive antennas. The possibility of evaluating different MIMO schemes is interesting for experimental and academic research.

The forth application focus on antenna measurements. The test-bed allows for several configurations regarding the spacing between antenna elements to be tested. It is also possible to perform measurements for different type of MIMO antennas.

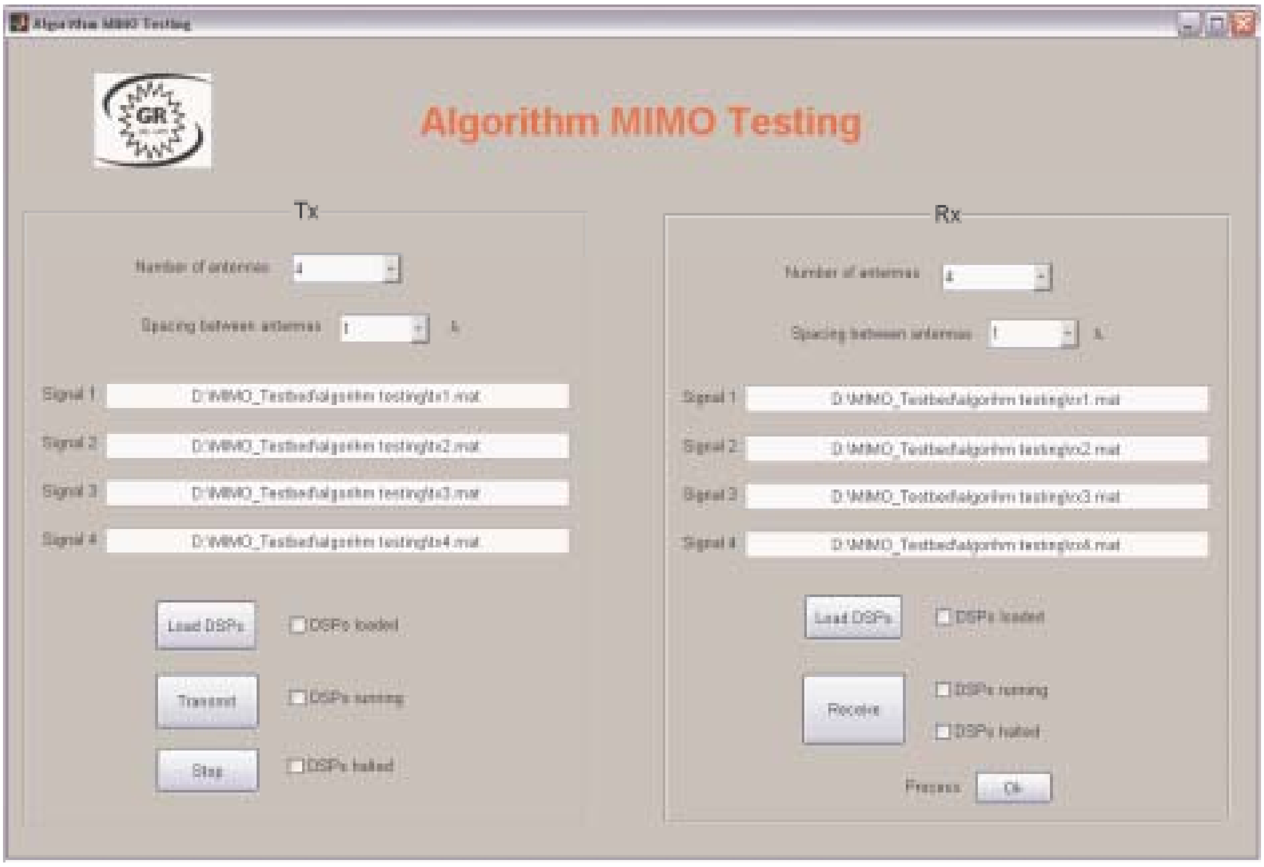


Figure 27. Main window of channel sounder application.

The work related to the MIMO test-bed development was presented to its major extension in the internal workpackage meeting in Athens, attracting the interest of many partners. In fact, the discussions during that meeting foster the visit of the PhD candidate Laura Garcia to KTH premises to perform channel measurements and collaborate with WP2.2-3 task 5 on antenna reference models [64].

The activity on UPM test-bed is foreseen to continue in ACE2 where the focus will be on exploiting the test-bed capabilities towards algorithm implementation and testing, channel measurements and educational purposes.

The work of KTH in the MUMS test-bed has focus on the implementation of several algorithms as well as upgrading some of the test-bed features as explained in more detail next.

The implementations "Spatially Multiplexed MIMO System" and "Smart Antenna Multiuser Algorithm" have been finalized. Initial results were presented in [59]. The test-bed has also been upgraded to work in 1800MHz band since there is less man-made noise in this band than in the previously used 450MHz frequency band. The new frequency band may also be closer to the frequencies where commercial implementations may be made. Moreover, it easier to prototype antennas for this band since patch antenna designs and similar become practical.

Spatially Multiplexed MIMO System

A prototype implementation of a 2x2 MIMO system employing adaptive modulation and spatial multiplexing on the KTH MUMS test-bed has been performed [62]. The system is targeted towards a low mobility scenario where channel state information can be accurately obtained and fed back to the transmitter and realizes 15bits/sec/Hz. There were practical issues imposed by the impairments of the hardware that had to be overcome in order to achieve results close to that of ideal simulations. First of all, the oscillators of the receivers and transmitters were not locked and therefore there was a substantial rotation of the signal constellations at the receiver. Due to a very limited RF bandwidth in the system the relative frequency error is as high as 20%. The frequency must be estimated without having acquired the exact synchronization. This is achieved by starting the transmission using a few dedicated pilot frames with a repetitive structure. This allows the frequency offset to be estimated from the auto-correlation of the received signal. The system employed chrystal-filters with a bandwidth just slightly larger bandwidth that of the transmitted waveform. The advantage of such a design is that the sampling rate of the ADC converters can be kept low. Furthermore, the linearity requirements are relaxed since the filters will block unwanted adjacent signals. The drawback of the design is that the narrow filters will introduce inter-symbol interference. Due to the drifting of the oscillators different the inter-symbol interference will also vary with time. Every crystal filter is also unique and therefore the channel between all transmitter and receiver antennas will be different. The distortion due to this imperfection is not significant at modulation constellation such as 16QAM and smaller. However, with high-order constellations, such as typically aimed for with MIMO solutions, the impairment is significant. To overcome this we need to perform equalization, which is not-trivial given that since we are transmitting two simultaneous streams. We have come up with a solution that does not involve the estimation where the equalizer coefficients for both receiver antennas and the equivalent frequency flat channel are calculated directly (without first estimating a multi-tap channel) from the received signal. The method optimizes the SNR (where residual the residual ISI is also included in the noise term) of the resulting frequency flat channel. The filters employ eleven taps and the straightforward numerical solution to the posed equalizer would require the solution of a generalized eigenvalue problem of dimension eleven by eleven. However, the equations are rewritten in a form that can be solved using a standard eigenvalue decomposition of size two. The equalizer also makes the system robust against synchronization errors. Note that if the clocks of transmitter and receiver are not locked, the synchronization will eventually slip. The performance of frequency and inter-symbol rejection is illustrated in Figure 28 where the SNR on the x-axis is obtained with a sinusoid input signal (the SNR of which is insensitive to inter-symbol interference, synchronization and carrier frequency offset) and the y-axis the signal to interference ratio as seen by the detector. The loss is 2dB for small SNR but increases with higher SNR.

The system employed a channel dependent pre-coding at the transmitter (a unitary matrix). To forward this information from the receiver to the transmitter an efficient encoding of the unitary matrix was developed. In addition to feedback of transmitter pre-coder information, the modulation of both streams was adaptively controlled from BSK to 512 xQAM. The system achieved a maximum of 15bits/sec/Hz and the double rate of a reference SISO system with the same modulation and equalization over most operating conditions.

Smart Antenna Multiuser Algorithm

In [63] an implementation of a system with interference cancellation at the transmitter on the KTH MUMS test-bed is described. In the implementation two 2-antenna transmitters (base-stations) and two 2-antenna receivers (mobiles) were used. The implementation was based on the paper [60]. This paper is by many considered as highly theoretical since global channel knowledge is assumed. However, in this implementation this requirement could actually be met due to the low Doppler rate of the scenario. The channel information was obtained so that the two (synchronized) base-stations transmitted training sequences one at a time. The mobile-stations then feed back their estimates of the channels through the feedback channels. The feedback channels are actually implemented using cables but nothing prevents these channels from being wireless. After this the base-stations have knowledge of all four wireless channels involved in the downlink (TX1->RX1, TX1->RX2, TX2->RX1, TX2->RX2), i.e. they have global channel knowledge. Armed with this information the weights can be calculated using the iterative procedure of [xxx]. The procedure is iterative as the weights for one base-station is fixed while the other is updated. Thus both base-stations will calculate the weights to be used by themselves but also the weights to be used by the other base-station (while this information is thrown away). Since the calculations are based on the same channel estimates the calculations in the two base-stations will be consistent. As a result of the optimization the receiver weights are also obtained. These weights are then quantized and sent to the receivers using BPSK to obtain high reliability. Finally, the actual transmission using these weights takes place. After one super-frame, the channels and weights are re-estimated.

The paper [60] is general in terms of the criterion function (which is related to the desired signal) and the constraint (which is related to the interference). In this implementation the criterion function is the total delivered power, which leads to transmission of a single spatial stream on the largest singular value of the channel and the constraint is the total power of the interference after combining at the co-channel users.

In order to make the system robust against ISA, frequency offsets and small changes of the channels a number of measures are taken. First the frequency is estimated from the training frames in the beginning of the super-frame. After having removed the frequency offset a seven-tap linear equalizer is estimated based on the training sequences. Linear equalizers work quite well on channels with small amount of inter-symbol interference such as encountered here. In order to solve for the equalizer coefficients a 7x7 QR factorization is needed. To compensate for small channel changes, the receiver re-modulates the symbols after detection and then re-estimates the effective scalar channel. This estimate is then filtered over a number of consecutive frames and used for compensation before detection. The results of running the system over large number of cases are shown in the figure below. As the results show the system with the proposed whitening at the transmitter and receiver (Prew) outperforms the SISO system and the system which uses only beam-forming without pre-whitening (BF). Simulation results showed a much smaller gain from the pre-whitening. The reason for this could be that the simulations assumed uncorrelated fading between all the four sub-channels of the MIMO channel while this may not have been the case in the measurement results.

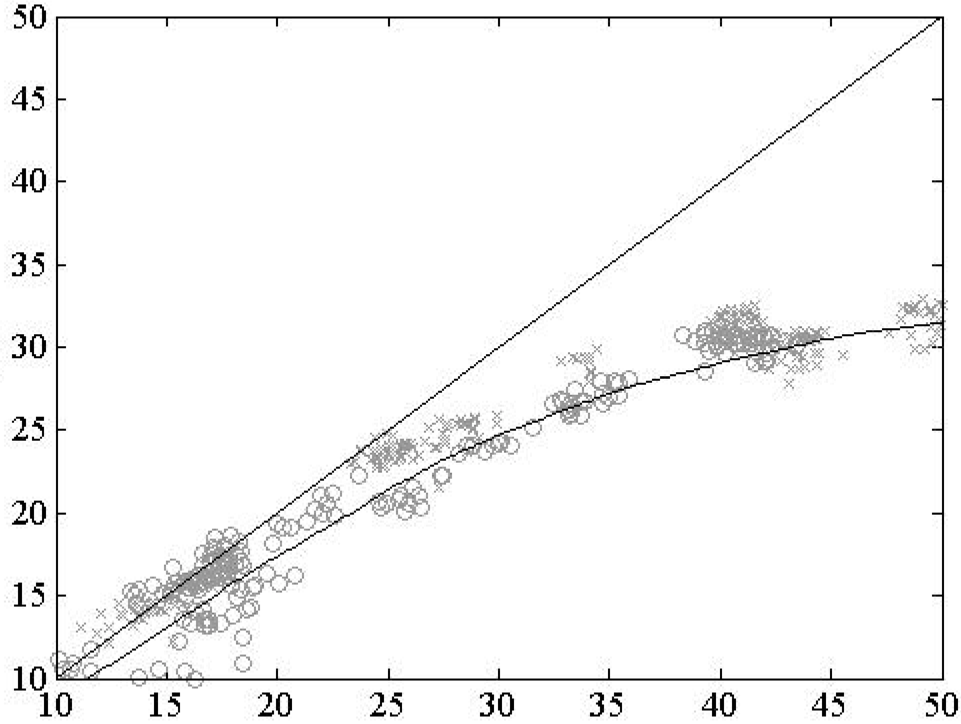


Figure 28. The achieved SNR (dB) versus the maximum achievable SNR (dB).

This work has been partially disseminated in an international conference paper and a journal paper, which full references are given bellow. Also a more extend internal specification document has been produced and distributed among ACE partners [43].

D. Samuelsson, J. Jaldén, P. Zetterberg and B. Ottersten, “Realization of a Spatially Multiplexed MIMO System”, EURASIP, Journal on Applied Signal Processing, March 2005.

X. Zhang, P. Svedman, H. Lundin and P. Zetterberg, “Implementation of a Smart Antenna Multiuser Algorithm on a DSP-Based Wireless MIMO Test-Bed”, Proceedings IEEE International Symposium on Personal Indoor and Mobile Radio Communications PIMRC, September 2005.

Future actions intend the implementation of MIMO antenna selection capabilities on MUMS test-bed, this work is envisioned to be closely developed jointly with the expertise of UPRC.

3. Advanced Receiver Structures

In this section research advances on receiver structures are presented, followed by a detailed description of the activities that took place in the workpackage WP2.2-3 related to this task. The joint research activities carried out by the participating partners have concentrated their efforts on channel estimation techniques, receiver design with special emphasis on iterative techniques and interference cancellation issues. The partners that have been interested and have actively collaborated in this task includes CTTC, IT, ICCS/NTUA and UPM.

The channel estimation problem has integrated the largest number of partners producing the higher number of contributions and interactions.

Table 2 is a sample of the identified research interest shared by three partners on this research gap. ICCS/NTUA, CTTC and IT have looked at channel estimation techniques for MIMO multicarrier systems. The research topic addressed by ICCS/NTUA considered a channel estimation algorithm for MC-CDMA system that follows a two stage approach: an initialization phase and a tracking phase, where the focus has been placed on the performance evaluation of the channel estimation algorithm and its impact on the overall performance taking into account imperfections and impairments caused by the RF stages in a real transmitter or receiver.

IT has also addressed the problem of channel estimation on a multicarrier system, focusing on two different access schemes MC-CDMA and SS-MC-MA. The proposed channel estimation schemes are pilot-aided, where two different approaches have been studied: one that uses only pilots for channel estimation and a second one that enhances the pilot-based channel estimates through data-aided tracking schemes. The work was motivated by and focused on the following aspects:

- provide robustness relatively to the channel environment
- allow computationally efficient implementations

The first item was addressed by considering an MMSE based approach which allows to explore the channel correlation either in the frequency or time domain, resorting to a three step-approach:

i) Start with an initial estimate using the simple LS algorithm

ii) Using the estimates provided in step i) compute an estimate of the channel autocorrelation function

$$\hat{\mathbf{R}}(n) = w_1 \hat{\mathbf{H}}_{LS}(n)\, \hat{\mathbf{H}}_{LS}^{H}(n) + w_2 \hat{\mathbf{R}}(n-1) \qquad \textbf{(Eq. 1)}$$

where n refers to the frame n, $\hat{\mathbf{H}}_{LS}(n)$ represents the LS estimates for frame n and w_1 and w_2 are filtering coefficients that weight the past information with the estimates for frame n. For the specific case of one-shot channel estimation i.e. estimates based only the current frame w_2=0.

iii) Using the estimate for the channel autocorrelation given by Eq. 1 perform the standard MMSE filtering operation,

$$\hat{\mathbf{H}}_{MMSE}(n) = \hat{\mathbf{R}}(n)\left(\hat{\mathbf{R}}(n) + \sigma_n^2 I\right)^{-1} \hat{\mathbf{H}}_{LS}(n) \qquad \textbf{(Eq. 2)}$$

where σ_n^2 is the noise variance at each time-frequency bin.

iv) Improve the estimate by recomputing the estimate of the autocorrelation using the channel estimates computed in step iii) and given by Eq. 2.

Table 2 Summary of identified partners research interest regarding channel estimation techniques

	ICCS/NTUA	IT	CTTC
Modulation and Access Schemes	MC-CDMA	MC-CDMA, MC-SSMA	DS-CDMA, MC-CDMA
Classes of Channels Estimation Techniques	a) Pilot-assisted b) Blind c) Hybrid	a) Pilot-based b) Iterative data-aided c) Differential modulation to minimize overhead	a) Iterative Joint channel estimation, symbol detection
Target Scenarios	Realistic / measured propagation environments	Simplified theoretical scenarios for preliminary evaluations. Realistic scenarios for proof of concept of the algorithms. Currently target scenarios are related to cellular networks at 5GHz with emphasis on the uplink	
Type of work		Analytical and simulations	
Modules available for simulations		Full link level MC-CDMA chain Specific CHEST algorithm Channel models: Generic SISO 3GPP2 model for MIMO. Most of the modules are available in SystemC (3GPP2 model in two step: 1st Matlab, 2nd System).	

The inclusion of the iterative step iv) was however found to provide only a marginal improvement for the channels considered and therefore the algorithm was restricted to the steps i) - iii). The algorithm was found to provide robustness relatively to variations or unknowns in the channel statistics but still requires a matrix inversion which can pose computational challenge for the cases where a large bandwidth, i.e a high number of subcarriers is considered in the MC-CDMA system (which will result in a high number of pilots to fulfil the Nyquist criteria in the frequency domain).

Therefore the second issue addressed was the problem of providing computationally efficient solutions. To address this goal the possibility of designing a Low-Rank MMSE estimator using the highest eigenvalues of the estimate of the autocorrelation function was considered. With such an approach no matrix inversion is needed. However, since only a partial characterization of the autocorrelation matrix is used, the algorithm exhibits an irreducible error floor. This is the main limitation on the complexity reduction achieved by MMSE low rank algorithm but its performance degradation can be limited by choosing a sufficient rank. For SNR<10 dB the low rank follows very closely the MMSE estimator based on the inversion of the autocorrelation matrix.

The algorithms have been applied to MC-CDMA and MC-SSMA systems for SISO and MIMO systems. In the MIMO case the estimation algorithm is a direct extension of the SISO case, i.e. consists in $Q \times R$ SISO channel estimation processes where Q and R denote the number of transmit and receive antennas, respectively. Therefore effort was devoted to devise schemes able exploit the spatial dimension in a more efficient way.

In fact although in MIMO channels there is a low correlation between the $Q \times R$ radio links if the antennas elements are sufficiently separated, the relative time delays, concerning the average power delay profile measured in each receiver antenna, are approximately the same. This feature can be used to improve the performance of the MIMO channel estimator. Therefore the spatial version of the channel estimator was improved through the following process:

- Use the $Q \times R$ estimates obtained through the process described above and obtain the time-domain response by applying an IFFT.
- Compute the average delay profile
- Search the N higher multipaths, where N is a design parameter.
- Zero padding: replace samples at locations other than the N selected peaks by zeros
- Perform an FFT to get the frequency domain response

With such an approach a significant noise reduction can be achieved.

CTTC has considered a semi-blind maximum likelihood (ML) channel estimation approach for MC-CDMA with code multiplexed pilots. According to this approach, training information is spread over all subcarriers and transmitted at the same time as traffic information. This configuration is usually more efficient in terms of spectral utilization. The performance of which is characterised via analytical derivations exploiting the properties of asymptotically large Fourier matrices, which allows to analytically characterize the ultimate symbol estimate quality in terms of a parameter related to its evolution through the iterations.

Iterative schemes has been considered under the framework of multi-resolution broadcasting applications, equalization and interference cancellation.

The application of iterative receivers for multi-resolution broadcasting applications has been investigated at CTTC. The basic idea of such encoding procedure is that receivers with poor signal reception can only decode the basic rate and receivers with higher quality can achieve higher resolution rates. A block diagram of the multi-resolution encoder is depicted in Figure 29 where the source encoder splits data into K independent streams which are fed to K independent channel encoders. Such schemes have the advantage of scalability and also provides additional robustness against channel variability. The proposed receiver consists of an interference cancellation stage followed by several single user decoders. The work performed has involved the performance analysis of the receiver based on variance transfer (VT) approximation and SNR gap to capacity approximation.

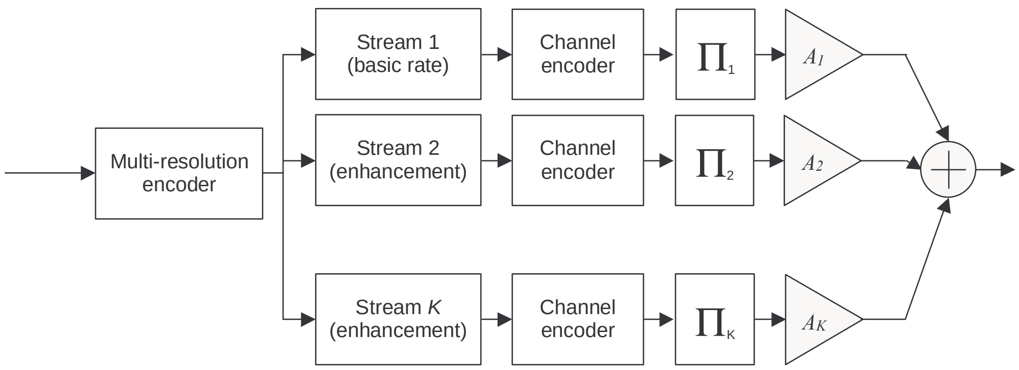


Figure 29. Multi-resolution encoder for broadcasting applications.

Interference Cancellation has been an item of research at IT and CTTC. The former addressed interference cancellation following a new frequency domain approach. A linear frequency domain canceller, based on a parallel structure, is proposed and evaluated under a UMTS-TDD multiple antenna framework. In the case of CTTC the interference canceller adopts a successive interference cancellation approach. This work extends a power distribution control scheme for MC-CDMA to any system that can be described by a generalized decision feedback equalizer structure.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Channel Estimation Strategies in Advanced Receiver Structures**

Authors: ICCS/NTUA

Participants: 18 people representing 8 partners from CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC.

Dates/Duration: 8-9 February 2005 at the internal workpackage meeting in Athens

Description: This activity involved a technical presentation given on MIMO channel estimation strategies for multicarrier schemes. Their importance on the total system performance has been highlighted through end-to-end system level computer simulations. Specifically, in advanced MIMO multicarrier transceiver structures that target throughput maximization, reliable channel estimation is a crucial issue that characterizes the performance of the whole system. The complexity of the channel estimation in MIMO multicarrier systems increases with the number of transmit/receive antennas, since the independent channels share the same bandwidth. Within the framework of this task a channel estimation algorithm has been evaluated on a complete system, taking into account imperfections and impairments caused by the RF stages in a real transmitter or receiver. Alamouti's STBC scheme has been used assuming constant fading over two consecutive OFDM symbols.

The channel Estimation stage is based mainly on the calculation of the channel transfer function (CTF) (frequency domain). The approach is divided in two phases, the initialization phase and the tracking phase. The initialization phase is implemented by the transmission of preamble signals from the different antennas that are orthogonal in frequency (even and odd subcarriers have been transmitted by the 1^{st} and 2^{nd} antenna respectively). The tracking phase of the estimation procedure is based on a scattered pilot-assisted Least Mean Square (LMS) algorithm. The space-time block decoding stage is based on the Alamouti scheme, applied on a per sub-carrier basis of the multicarrier system. The evaluation is performed on SUI channel models and the results indicate that even small system imperfections, especially phase distortions, can cause large BER degradations.

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Channel Estimation for Uplink MC-CDMA**

Authors: IT

Participants: 18 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC.

Dates/Duration: 8-9 February 2005 at the internal workpackage meeting in Athens

Description: Channel estimation for uplink MC-CDMA and SS-MC-MA, pilot-aided versus pilot and data aided channel estimations. In this presentation open issues on channel estimation for MC-CDMA and SS-MC-MA were presented. For both cases it was considered a pilot based approach for the problem of channel estimation, where the frame considered was the one issued in the IST FP6 4MORE project (http://4more.av.it.pt). The pilots are used to get an estimate of the frequency domain channel coefficients, using the so-called robust MMSE approach described in [11], which allows operation without a priori knowledge of the channel statistics. A proposal to improve the algorithms, through an iterative sequential procedure where the data symbols are regenerated, and then using these regenerated estimates as true values an estimate of the channel coefficients is obtained which is combined with the ones obtained using the pilots to reduce the error and improve the BER. The results have shown that improvement can be obtained for SS-MC-MA since there is no multiple access interference (MAI), but for MC-CDMA due to the MAI simple detection circuits produce for high loads (in terms of the number of users) unreliable data symbols which are not accurate enough to improve the channel estimates. Currently work is on going on combining robust MMSE with more sophisticated detection schemes for MC-CDMA. Part of the results were presented afterwards in [1] and [2]. Discussion allowed to identify common interests with NTUA.

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange. Part of the work has been disseminated in the papers,

P. Marques, Y. Yi and A. Gameiro, "Performance Evaluation of Channel Estimation Techniques for a beyond 3G Systems", MWCN2005, Marrakech, Morocco, Sept. 2005.

P. Marques, A. Pereira and A. Gameiro, "Pilot and data aided channel estimation for uplink MC-CDMA mobile systems", IST SUMMIT 2005, Dresden, Germany, June 2005

Further research on iterative joint detection – channel estimation for MC-CDMA is envisaged with emphasis on complexity issues. Refine possible collaboration with NTUA.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Uplink MIMO Channel Estimation for Beyond 3G Systems**

Authors: IT

Description: Multiple input multiple output antennas (MIMO) can be used in B3G systems to improve communication quality and capacity. The receiver should know the MIMO channel to achieve coherent signal detection. In this paper, we propose an efficient channel estimation technique for MC-CDMA systems and MIMO uplink transmission. The proposed MIMO channel estimator results of a simple extension of SISO channel estimator for each receiver antenna. The SISO channel estimator adopted is the robust minimum mean-squared error (MMSE) that does not require a priori knowledge of the channel statistics. The performance of the proposed MIMO channel estimation algorithm is demonstrated by computer simulation for B3G typical scenarios.

Outcome and future actions: As a result of developing the work initiated in Athens internal workshop the following papers were presented at international conferences in 2005.

P. Marques and A. Gameiro, "Uplink MIMO Channel Estimation for Beyond 3G Systems", Fifth IEE International Conference on 3G Mobile Communication Technologies, London, UK, Oct 2004.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Semi-blind Maximum Likelihood Channel Estimation**

Authors: CTTC

Participants: 18 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC.

Dates/Duration: 8-9 February 2005 at the internal workpackage meeting in Athens

Description: This activity consisted of a technical presentation of semi-blind maximum likelihood (ML) channel estimation for MC-CDMA with code-multiplexed pilots.
The objective has been to investigate the performance of an iterative semi-blind channel estimator for a MC-CDMA system. The presented results derive a deterministic description of the convergence of the estimator. The authors shortly presented the performance of an iterative ML channel estimation algorithm for MC-CDMA that exploits the code-multiplexing of training pilots. The considered asymptotic analysis allows to analytically characterize the ultimate symbol estimate quality in terms of a parameter related to its evolution through the iterations. The presented analytical characterization can further be employed for detection purposes, whereby it turns out to be of most benefit if applied to non constant-amplitude modulations like M-ary QAM.

The integration within ACE aimed at any partner willing to collaborate.

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange. Future work is on the direction of employing these techniques for detection purposes, whereby it turns out to be of most benefit if applied to non constant-amplitude modulations like M-ary QAM.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Semi-blind Channel Estimation for Multicode CDMA Systems**

Authors: CTTC

Description: This paper is the result of further development of the open problems presented at the internal workshop in Athens. An iterative ML channel estimator for MC-CDMA systems with code-multiplexed training has been proposed in the paper. Its performance has been studied by using results from the asymptotics of Fourier matrices with dimensions growing without bound with a constant ratio where the main results are summarized next.
In a MC-CDMA system with simultaneous transmission of code-multiplexed data and training pilots over N subcarriers, the received signal can be expressed as

$$\mathbf{y} = \left(\mathbf{D}_s + \mathbf{D}_p\right)\mathbf{G}^H\mathbf{h} + \mathbf{n}$$

where $\mathbf{D}_s$ is a diagonal matrix containing the spread data symbols **Cs**, with **C** being the signature matrix, $\mathbf{D}_p$ is a diagonal matrix containing the pilot symbols, $\mathbf{G}^H$ is a skinny matrix with the first L columns of the Hermitian Fourier matrix, **h** models the frequency dispersive channel impulse response with unknown deterministic entries and **n** denotes the background Gaussian noise over the N subcarriers. Equivalently,

$$\mathbf{y}=\mathbf{D}_H(\mathbf{Cs}+\mathbf{p})+\mathbf{n}$$

where $\mathbf{D}_H = Diag(\mathbf{G}^H\mathbf{h})$. The ML estimators for both data and channel impulse response can be obtained by minimizing the following negative log-likelihood function:

$$N\ln(\pi\sigma^2)+\frac{1}{\sigma^2}\left\|\mathbf{y}-(\mathbf{D}_s+\mathbf{D}_p)\mathbf{G}^H\mathbf{h}\right\|_2^2$$

Since the objective function is separately quadratic in its two unknown variables both parameters can be iteratively estimated as

$$\hat{\mathbf{h}}_k=\left(\mathbf{G}\hat{\mathbf{D}}^H\hat{\mathbf{D}}\mathbf{G}^H\right)^{-1}\mathbf{G}\hat{\mathbf{D}}^H\mathbf{y}$$

where $\hat{\mathbf{D}}=\hat{\mathbf{D}}_s+\mathbf{D}_p$, with $\hat{\mathbf{\Lambda}}_s$ resulting from replacing **s** by its estimate $\hat{\mathbf{s}}$, and

$$\hat{\mathbf{s}}_k=\left(\mathbf{C}\hat{\mathbf{D}}_H^H\hat{\mathbf{D}}_H\mathbf{C}\right)^{-1}\mathbf{C}\hat{\mathbf{D}}_H^H(\mathbf{y}-\hat{\mathbf{D}}_H\mathbf{p})$$

The fast convergence properties of the techniques used for our large system analysis allow for a good match between the analytical results and the system performance in realistic non-asymptotic situations. Our results are quite general because they do not depend on signature sequences or pilot structures and nothing needs to be assumed regarding the distribution of the channel. This asymptotic analysis allows us to (asymptotically) characterize the estimator analytically in terms of a parameter related to the evolution through the iterations of the symbol estimate. Simulations were used to verify the rapid convergence of the proposed algorithm to a final value that can be properly localized by using the characterization of the evolution parameter. This result can further be applied for detection purposes directly, and non-constant amplitude modulations, like M-ary-QAM, were identified as prospective candidates since the selection of decision regions in such constellations is much more sensitive to errors.

Outcome and future actions: As a result the following paper of developing the work initiated in Athens internal workshop the following paper was presented at the Signal Processing Workshop in 2005.

F. Rubio, X. Mestre, “Semi-blind ML channel estimation for MC-CDMA systems with code-multiplexed pilots”, VI IEEE Workshop on Signal Processing Advances in Wireless Communications, New York (USA) June.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Iterative Multiuser Receiver for Multi-resolution Broadcasting**

Authors: CTTC

Description: An iterative multiuser receiver is proposed to decode a broadcast transmission with multiple rates. Multiple rates are used to provide a low-rate, minimum quality version to receivers with poor SNR and one or more higher definition versions to receivers with higher SNR. In the setup of this paper, different rates are encoded separately and detected by means of iterative interference cancellation and decoding. It is shown that such receiver implements a successive decoding strategy, and its performance is evaluated by the code SNR gap to channel capacity, which is also used to derive the power distribution among different rates. Finally, results are verified by simulation.

Outcome and future actions: Dissemination in,

C. Ibars and S. Pfletschinger, "Iterative Multiuser Receiver for Multi-resolution Broadcasting," Proc. 38th Asilomar conference on Signals, Systems and Computers, Pacific Grove, CA, Nov. 2004.

Future work will look at code design analysis.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Multi-Sensor Frequency Domain Multiple Access Interference Canceller**

Authors: IT

Description: Direct Sequence Code Division Multiple Access (DS-CDMA) signals exhibit cyclostationary properties which imply a redundancy between frequency components separated by multiples of the symbol rate. In this paper a Multiple Access Interference Canceller (Frequency Shift Canceller) that exploits this property is presented. This linear frequency domain canceller operates on the spread signal in such a way that the interference and the noise at its output is minimized (Minimum Mean Squared Error Criterium). The Frequency Shift Canceller (FSC) performance was evaluated for a UMTS-TDD scenario and multisensor configurations, where the cases of diversity and beamforming were considered. All these configurations are evaluated concatenated with a parallel interference canceller (PIC-2D). The results are benchmarked against the performance of the conventional RAKE-2D detector, the conventional PIC-2D detector and single user scenario, and we observe considerable performance gains with the FSC specially for the diversity case and a performance close to the single user case when it was evaluated jointly with PIC-2D.

Outcome and future actions: Dissemination in a journal paper,

L. Gonçalves and A. Gameiro, "Multi-Sensor Frequency Domain Multiple Access Interference Canceller for", Accepted for publication at the European Trans Telec.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Equal SNR Power Distribution for Generalized DFE Structures**

Authors: CTTC

Description: Successive interference cancellation within a block of symbols suffering inter-block interference can be described by the generalized decision feedback equalizer (GDFE) structure. In this paper a power distribution (PD) yielding equal SNR for all symbols within a block is determined for the minimum mean square error GDFE. Results using such PD for MIMO-CDMA, OFDM, and block data transmission with successive interference cancellation receivers, all of which can be described by the GDFE, are provided. Numerical results show the power gain advantage over linear receivers with equal SNR PD.

Outcome and future actions: Disseminations in,

C. Ibars, M. Tan and Y. Bar-Ness, "Equal SNR Power Distribution for Generalized DFE Structures," Proc. Wireless Communications and Networking Conference (WPMC), Abano Terme, Italy, Sept. 2004.

4. Reconfigurable/Adaptive Transmission Schemes

This section relates to research activities addressing aspects on reconfigurable and adaptive transmission schemes. Adaptive schemes has been investigated within the framework of the degree of available channel knowledge at the transmitter. The joint research activities have been structured in two main issues: transmit architectures with partial channel knowledge and reconfigurable transceivers with linear pre-coding. A technical description of the main contributions and advances on the investigated topics are presented through the description of the activities that took place in the workpackage WP2.2-3 related to this task.

Several transmit architectures considering either imperfect channel knowledge or different levels of partial channel state information have been addressed. The performance of an optimum transmit filter of a multiple input multiple output system when only channel modulus is known at the transmitter has been analysed and evaluated, with results provided on the Ergodic capacity of a MIMO uncorrelated flat fading channel with perfect channel state information at the receiver and partial channel state information at the transmitter. In this case it has been found that a simple optimum power allocation achieves capacity. For the 2 by 2 case, close form expressions are derived and the power allocation policy described graphically in Figure 30.

Adaptive schemes were also assessed with respect higher level performance parameters. In particular, re-configurable transmission aspects were considered for DS-CDMA systems with adaptive modulation from a MAC layer performance point of view with a feedback protocol. Adaptation is implemented based on SIR measurements. Differential approaches has been proposed for scenarios where no channel state information is available to the transmitter. A new scheme intends to overcome the limitations of Cayley differential space-time codes related to the achievable diversity gain. In this direction, a combined Caley-TAST (Threaded Algebraic Space-Time) coding scheme is proposed to achieve full spatial diversity gains in an OFDM-MIMO system. This scheme also allows for an easier code optimization since a parameterization process of the information data is shown directly in the Hermitian matrix, in contrast to the regular Cayley code that relies on pre-selected basis matrices.

Beamforming performance degradation due to imperfect channel knowledge has been investigated based on eigenvector perturbation theory. Easily computable approximations are given for the average signal to noise ratio loss when an estimate of the channel is available. The performance degradation of imperfect beamforming is then particularized for a LMMSE channel estimator taking into consideration power constraints. Results has indicated that if a sufficiently accurate channel estimate is available to the transmitter, beamforming under imperfect CSI does not suffer considerable losses. This results relates to previous work where it has been found that in terms of capacity beamforming is close to optimal for relatively good feedback CSI information.

Under the scope of linear pre-processing, partners have addressed several research items including spatial filters for multicode DS-CDMA, linear pre-equalization forMC-CDMA and linear-precoding under a re-configurable framework. The asymptotic performance evaluation of several code-reference spatial filters for multicode DS-CDMA has shown that the projector onto the span of the codes of the desired users has better performance than the well known matched filter and decorrelator, since the later filters saturate for increasing values of the input SNR.

Extensive work has been carried out within the workapckage on space-time-frequency pre-equalization for the downlink of MC-CDMA based systems. The motivation for such a work is threefold:

1. The use of channel state information at the transmitter side can improve significantly the performance. In fact, results have shown that a multiuser transmitter design significantly outperforms a multiser receiver design (which in any case would be difficult to implement at the mobile) for the broadband channels of interest.
2. A multiuser pre-equalization design allows to move the complexity associated with the equalization function from the receiver to the transmitter. This is of parameout importance for the downlink of cellular systems since it allows to reduce the complexity of the mobile which has much higher stringent requirements that the base station (BS) in terms of computational complexity and power consumption.

With time division duplexing (TDD) there is inherent CSI at the BS which can be therefore exploited. This CSI is reliable for low to moderate speed environments.

Finally, linear pre-coding schemes for space-time block coded systems have been investigated with the purpose of achieving re-configurability to antenna correlation and channel state information reliability by employing a transmission scheme adaptive to channel conditions. The main idea of an optimal linear pre-coder is to improve the performance of a space-time coded system by forcing transmission on the nonzero eigenmodes of the transmit antenna correlation matrix. The proposed schemes assume to have some knowledge of the second-order statistics of the channel. Therefore it does not have to track fast fading; it only tracks the slowly varying antenna correlations, which reduces the feedback channel requirements.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Optimum Transmit Architecture of a MIMO System under Modulus Channel Knowledge at the Transmitter**

Authors: CTTC

Participants: 12 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC; and 1 external organization: Sony Ericsson.

Dates/Duration: 11th November 2004 at the internal workpackage meeting in Nice

Description: A technical discussion on optimum transmit architectures for MIMO systems was addressed aiming at introducing the work initiated in this field by the partner CTTC and stimulating the collaboration within others partners. The presentation introduced the aim of the investigation and described the approach taken as well as highlighted the topics of possible collaboration, thus

- The goal has been to investigate different optimal MIMO configurations under partial or imperfect Channel State Information. In particular, to find what is the optimum transmit filter **W** if only channel modulus is known at the transmitter. The assumption of such partial channel state information available at the transmitter is motivated by the amplitude calibration present in TDD mode and the low rate feedback required.
- The intended approach shall be via analytical derivations and, possibly, supporting simulations.
- The expect results included to obtain a more accurate description of the optimum transmission schemes under some conditions of partial CSI.

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Optimum Transmit Architectures for MIMO Systems under Partial Channel Knowledge**

Authors: CTTC

Description: In this paper, we study the Ergodic capacity of a multiple input multiple output (MIMO) uncorrelated flat fading channel with perfect channel state information at the receiver and partial channel state information at the transmitter. We focus our attention on the case where the transmitter is informed only with the modulus of the channel matrix coefficients. First, we prove that a simple power allocation strategy among transmitting antennas is the optimal scheme, in the sense that is a capacity achieving architecture. Next, for the particular case where only two antennas are used at each communication end, we derive closed form expressions for the Ergodic capacity and the optimal power assigned to each antenna.

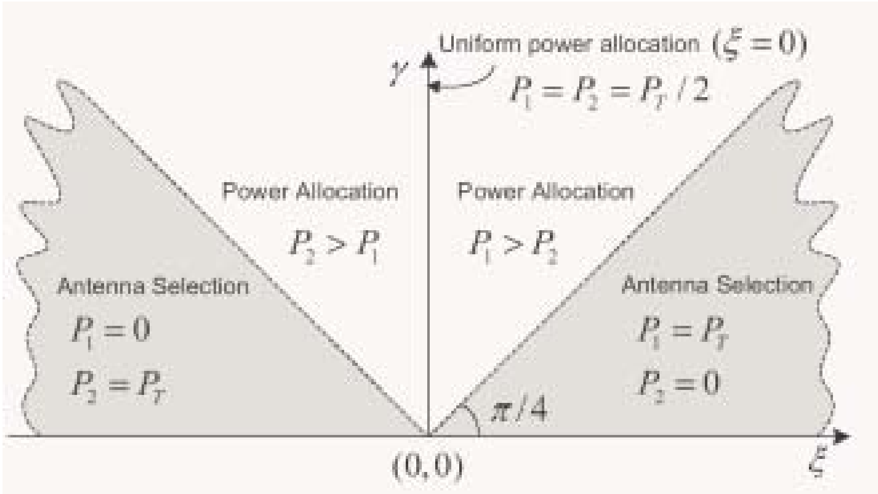


Figure 30. Graphical scheme of the optimal power allocation as a function of parameters γ andξ (function of channel amplitudes).

Outcome and future actions: Dissemination in,

M. Payaró, X. Mestre, and M. A. Lagunas, "Optimum Transmit Architecture of a MIMO System under Modulus Channel Knowledge at the Transmitter," in Proc. IEEE Information Theory Workshop (ITW'04), San Antonio, TX (USA), October 2004. ISBN 0-7803-8721-X.

M. Payaró, X. Mestre, A.I. Pérez-Neira, and M. A. Lagunas, "On Power Allocation under Phase Uncertainty in MIMO Systems," in Proc. Winterschool on Coding and Information Theory. Bratislava, Slovakia. February 20-25, 2005. ISBN 3-902477-01-6.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Beamforming with Imperfect Channel Knowledge**

Authors: CTTC

Description: This work analyses the performance degradation of beamforming due to imperfect channel knowledge based on eigenvector perturbation theory. Easily computable approximations are given for the average signal to noise ratio loss when an estimate of the channel is available. The performance degradation of imperfect beamforming is then later assessed for LMMSE channel estimation taking into consideration power constraints. Approximations for the performance degradation in terms of signal to noise ratio are derived. Based on perturbation theory for eigenvectors we obtained an approximation to the signal to noise ratio loss. The approximation requires the knowledge of the projection of the perturbation matrix over the eigenspace of the true channel. The perturbation matrix depends on the true channel and the estimation error. If the perturbation matrix is the identity matrix there will be no loss. In this case the approximation will only involve the inner product between the eigenvectors of the true channel which is zero since the eigenvectors are orthogonal. The perturbation matrix destroys the orthogonality. It applies a linear transformation to the principal eigenvector which is no longer guaranteed to be orthogonal to the rest of eigenvectors. The main difficulty is to determine the exact projection of the transformed principal eigenvector onto the rest of channel eigen-modes. This remains an open problem.

To simplify the problem we focus on the average performance degradation and approximate the mean receive SNR loss. In this case the approximation is only dependent on the eigenvalues and the relative separation between them, the variance of the estimation error and the system dimensions via the number of receive antennas. The approximation indicates that increasing the number of receive antennas augments the SNR loss. This was confirmed by the numerical results.

The performance degradation of imperfect beamforming has also been assessed when a power constraint is taken into consideration. In a real scenario some form of channel estimation method is utilised to obtain the CSI. We consider a training based channel estimation solution and studied beamforming under certain power constraints. When the total available power is fixed and shared between transmission of pilot symbols and information data symbols, simulations indicates that we should carefully evaluate which is the optimum power distribution. From BER performance simulated curves we see that the system suffers more from decreasing the power available to transmit the information than from erroneously stearing the beamformer.

Results indicate that if a sufficiently accurate channel estimate is available to the transmitter, beamforming under imperfect CSI does not suffer considerable losses. This results relates to previous workwhere it has been found that in terms of capacity beamforming is close to optimal for relatively good feedback CSI information.

Outcome and future actions: Dissemination in,

M. Navarro, and A. Grant, "Beamforming with Imperfect Channel Knowledge: Performance Degradation Analysis based on Perturbation Theory," in Proc. IEEE Sensor Array Workshop (SAM'04), Sitges, Barcelona (Spain), July 2004.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Code-reference spatial filters for multicode DS/CDMA**

Authors: CTTC

Participants: 12 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC; and 1 external organization: Sony Ericsson.

Dates/Duration: 11th November 2004 at the internal workpackage meeting in Nice.

Description: Another technical discussion aiming at fostering collaboration with CTTC was on field on asymptotic analysis to characterise the performance of code-reference beamforming schemes for DS-CDMA systems. The presentation introduced the aim of the investigation and described the followed approach as well as some initial results:

- The objective of this work has been to analyze, using random matrix theory, the performance of different code-reference beamforming schemes. We consider beamforming strategies applied to multi-code DS-CDMA architectures.
- The approach targets the use of random matrix theory, since the asymptotic behaviour for a large system can easily be characterized. The approach is to compare the Spatial Covariance Matrix before and after enhancing the signal of the desired user, so that its spatial structure is revealed.
- The expected results will include analytical derivations supported by simulations.

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Asymptotic Performance and Code-Reference Spatial Filters for Multicode DS-CDMA**

Authors: CTTC

Description: After the preliminary results presented in Nice, the results on code-reference spatial filtering for multirate DS/CDMA has been disseminated in a conference paper. The asymptotic performance of three spatial filters, respectively based on the matched filter, the decorrelator and a projector onto the span of the codes of the desired user, is derived, assuming that both the maximum spreading factor and the number of parallel code sequences increase without bound at the same rate. The three methods provide the solution for the beamvector in a single eigenvalue computation, avoiding the use of iterative techniques. A superior performance of the projecting filter against both correlating solutions is revealed: the performance of the last two filters saturates for increasing values of the input SNR, whereas the first solution is able to sustain an increasingly high output SINR.

Outcome and future actions: Dissemination in,

F. Rubio, X. Mestre, "Asymptotic performance of code-reference spatial filters for multicode DS/CDMA", IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2005). Philadelphia (USA), March 18-23, 2005.

F. Rubio, X. Mestre, "A comparative study of different self-reference beamforming architectures for multicode DS/CDMA", XI National Symposium of Radio Science Poznan Center of Science. Poznan (Poland) April 7-8, 2005.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Re-configurable Transmission Schemes – Adaptive Modulation for 3G CDMA Systems**

Authors: UPRC, ICCS/NTUA

Participants: 12 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC; and 1 external organization: Sony Ericsson.

Dates/Duration: 11th November 2004 at the internal workpackage meeting in Nice

Description: This technical presentation took place in the WP meeting in Nice, France, on 11th of November 2004, in the framework of JINA 2004, where ACE organized a parallel session. In this meeting, UPRC presented results on re-configurable transmission schemes. In the presentation a description of 3G simulation models and more specifically a description of available SPW models for W-CDMA were given for three scenarios:

- Uplink with/without STTD
- Downlink with/without STTD
- High Speed Downlink Packet Access (HSDPA) with/without STTD

It also included a description of available SPW models for CDMA2000/3GPP2 in the following two cases:

- Uplink with ideal power control
- Downlink with ideal power control and multiple users

Finally, an extension was proposed concerning MAC layer performance (Frame Error Rate) with feedback protocol. This proposal included the use of adaptive modulation based on SIR measurements (channel condition) with/without STTD.

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Re-configuration Strategies**

Authors: UPM

Participants: 18 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC.

Dates/Duration: 8-9 February 2005 at the internal workpackage meeting in Athens.

Description: High data rate requirement is becoming an essential demand for many applications, especially in next generation wireless systems. Recent researches have proven that Orthogonal Frequency Division Multiplexing (OFDM) modulation is a promising technology in the future high data rate wireless systems. In OFDM modulation the entire channel is divided into many narrow parallel sub-channels, which in effect will increase the symbol duration and reduce the ISI caused by multipath fading.

The performance of the OFDM system could be enhanced further when combined with Multiple Input Multiple Output (MIMO) antenna arrangement.

The bandwidth limitation is considered as the main obstacle in achieving the desired transmission rates. The diversity technique implemented by the multiple transmit and receive antennas has proven to be a good solution for the spectrum limitation. The channels formed by this diversity technique are known as Multiple Input Multiple Output MIMO channels. It was found that MIMO channels provide higher capacity when compared with the traditional SISO (Single Input Single Output) channels.

The transmit diversity based on Space-time coding is very important when using MIMO systems. The code design could be selected based on the channel estimation possibility. When the channel estimation is impossible, or the channel is varying rapidly, then a differential space-time code is an excellent coding choice.

The Cayley differential space-time code, used in previous work, is part of the unitary block codes. The reason of using Cayley Code is the excellent features that it provides to the system. Cayley differential space-time codes allow efficient and effective high-rate data transmission in multi antenna communication systems, with reasonable encoder and decoder complexity. Unfortunately, Cayley differential codes have the disadvantage of not providing full spatial diversity. In order to obtain full diversity, one solution is based on the Threaded Algebraic Space-time Coding (TAST) in conjunction with the Cayley differential codes. The Cayley code based on the TAST framework shall be modified and optimized to adapt the differential OFDM-MIMO system.

The main advantages of the Cayley-TAST code over the regular Cayley code are:

- Better performance due to the full spatial diversity,

- Parameterization process of the information data is shown directly in the Hermitian matrix, in contrast to the regular Cayley code that relies on preselected basis matrices. This reflects on making it easier to optimize the code matrix.

The Cayley-TAST code could be used to propose a reconfigurable MIMO transceiver. The code can be optimized for various channel conditions, producing different code parameters, which are calculated and stored in the transmitter and to be sent to the receiver. The receiver will update the transmitter about the channel condition after several packets of transmission (as needed!). Consequently, the transmitter will select the optimum code that is proper for that specific channel condition. This will improve the system performance due to the code adaptive feature. The usage of Cayley-TAST code reduces the information sent to the receiver just to two parameters: ϕ and γ.

An example of the code parameter optimization for narrow band channel condition is shown in Figure 31, Figure 32 and Figure 33. The transmitter requires the values of ϕ=0.2 and γ=0.5 in order to achieve the best performance at the receiver for that specific channel condition.

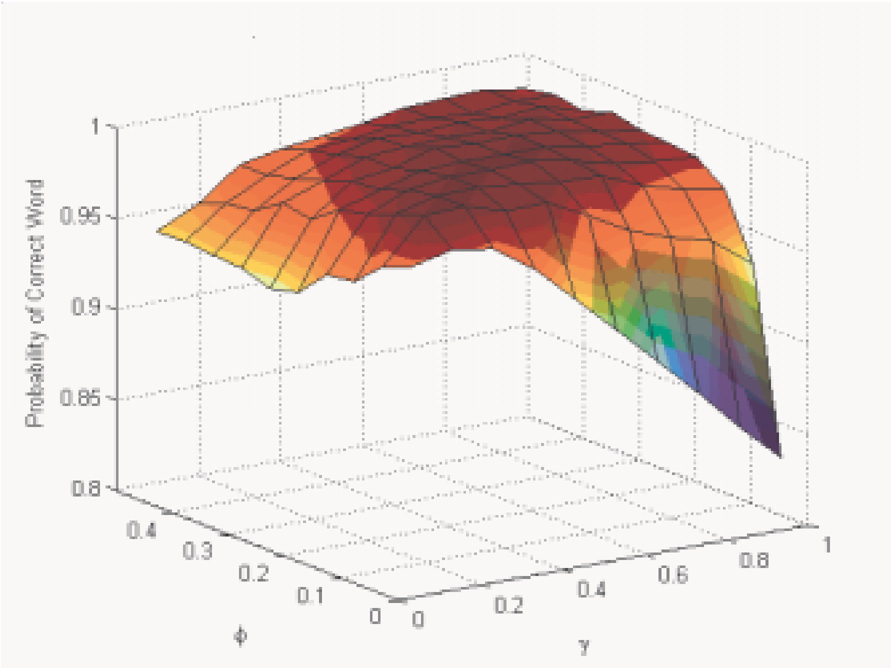


Figure 31. Probability of Correct Word vs. Code parameters ϕ and γ.

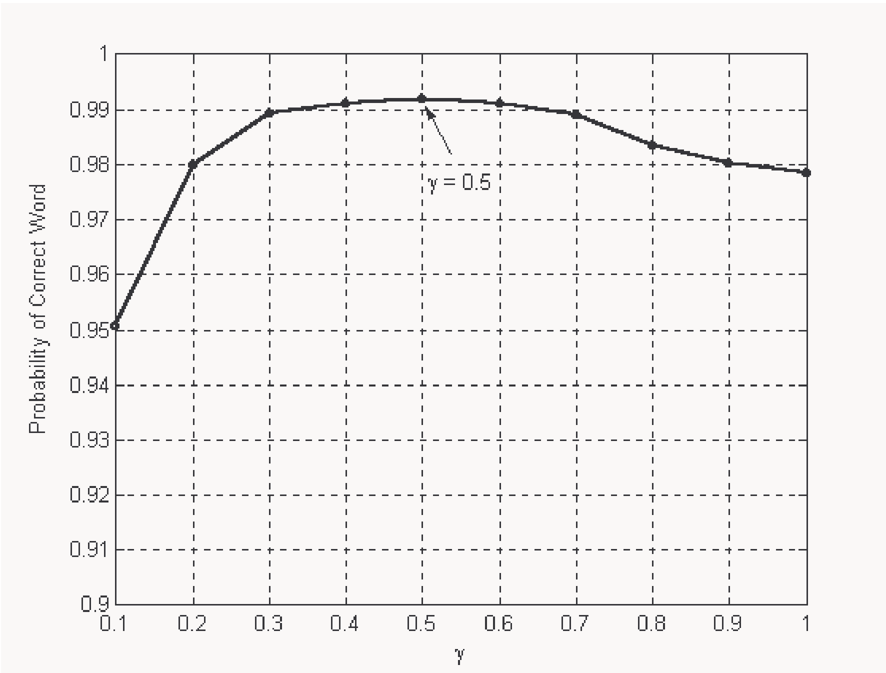


Figure 32. Probability of Correct Word vs. code parameter γ.

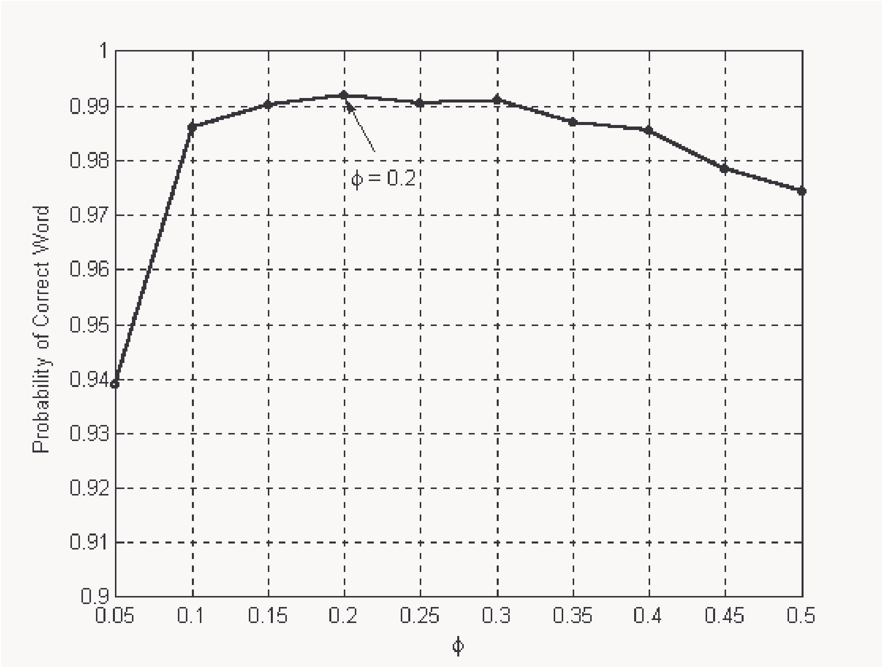


Figure 33. Probability of Correct Word vs. code parameter ϕ.

Outcome and future actions: Dissemination in an international conference paper,

A. Qatawneh, L. de Haro Ariet , OFDM-MIMO system using Cayley differential unitary space time coding, Sensor Array and Multichannel Signal Processing Workshop, SAM 2004, 18-21 July 2004, Sitges (Spain).

Activity type: ***Dissemination activity – Journal Paper***

Addressed research topic: **Finite Sample effect on Minimum Variance Beamformers**

Authors: CTTC

Description: Minimum variance beamformers are usually complemented with diagonal loading techniques in order to provide robustness against several impairments such as imprecise knowledge of the steering vector or finite sample size effects. In this paper, we concentrate on this last application of diagonal loading techniques, i.e. we assume that the steering vector is perfectly known, and that diagonal loading is used to alleviate the finite sample size impairments.

Our analysis is asymptotic in the sense that we assume that both the number of antennas and the number of samples are high but have the same order of magnitude. Borrowing some results of random matrix theory, we first derive a deterministic expression that describes the asymptotic signal to noise plus interference ratio (SINR) at the output of the diagonally loaded beamformer. Then, making use of the statistical theory of large observations (also known as general statistical analysis or G-analysis), we derive an estimator of the optimum loading factor that is consistent when both the number of antennas and the sample size increase without bound at the same rate. Thanks to that, the estimator has an excellent performance even in situations where the quotient between the number of observations is low relative to the number of elements of the array.

Outcome and future actions: Dissemination in the journal paper,

X. Mestre, M.A. Lagunas, "Finite sample size effect on minimum variance beamformers: optimum diagonal loading factor for large arrays", IEEE Transactions on Signal Processing, pending publication.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Pre-equalization for MC-CDMA**

Authors: IT

Participants: 18 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC.

Dates/Duration: 8-9 February 2005 at the internal workpackage meeting in Athens

Description: The activity included a presentation intending to describe the recent work carried out at IT on pre-equalization. The presentation aimed to introduce the benefits and also to point out some drawbacks related to pre-equalization in the context of MIMO systems, considering MC-CDMA as the access technique. It was pointed out that MC-CDMA combines efficiently OFDM and CDMA, but the user capacity is essential limited by MAI, and therefore in such context, pre-filtering algorithms that allow to format the transmitted signal so that MAI is removed at all mobile terminals (MTs) are of interest. In fact they have been shown to provide superior performance when compared against multiuser detection which in either case is difficult to implement at the mobile. Therefore the motivation for pre-equalization comes from two points of view: performance improvement and complexity reduction at the mobile terminal by moving some of the most complex functions to the base station.
The main drawback is obviously the fact that the channel must be known at the BS. The more recent work carried at IT focused on the combination of STBC with pre-filtering, where the former is intended to provide diversity and the second to reduce the MAI. This was the main core of the presentation where numerical results with a joint Alamouti space time coding and zero forcing pre-equalization were presented. It was show that this joint algorithm significantly outperforms conventional STBC schemes (Alamouti, Tarokh) when these are combined with single user detectors (ZF, MMSE).

The objective has been to undertake further research on this topic by considering the use of space coding in the frequency domain (namely SFBC) and extend the work to trellis codes. Part of the results presented were extended and presented in [3][4][5].

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Pre-filtering Techniques for MISO TDD Downlink MC-CDMA Systems**

Authors: IT

Description: This work considers two pre-equalization techniques for the downlink time division duplex MC-CDMA system: space-time block coding with a pre-filtering technique and space-frequency blocking with pre-filtering. The scenarios considered includes a MISO system with multiple antennas at the base station and single antenna at the mobile, motivated by complexity constraints in the target scenarios where the use of multiple antennas is more affordable at the base station than at the mobile terminal.

The design criteria considered is a zero-forcing one intended to remove the MAI at the mobiles. This choice was motivated by the fact that if enough degrees of freedom are available (which is true in most cases dealing with multiple transmit antennas) the degradation relative to a criteria aimed at minimizing some metric related to SINR is negligible, and the zero forcing criteria does not require knowledge at the BS of the noise level at the mobile and allows to decouple the power estimation problem from the equalization one. None of these aspects is true with an SINR based metric.

The pre-equalization schemes developed considered either:

- Pre-equalization for conventional single user receive structures, namely simple de-spreading which does not require channel estimation at the mobile and EGC (equal gain combiner) which only requires phase equalization at the mobile (i.e.. the amplitude equalization is performed at the BS while the phase equalization is performed in part at the mobile), and
- Combination of space-time-frequency-block codes (STFBC) with pre-equalization.

This latter option was motivated by the fact that STBC provides diversity but is significantly affected by MAI which is always one of the limiting performance factors in CDMA systems, while pre-equalization allows to eliminate the MAI. For the case of spatial block coding the two options of joint space and time and joint space frequency were considered, where the latter scheme has the advantage of reducing the duration of the time interval over which the channel must be considered invariant for the STBFC decoding scheme to perform adequately.

The block diagram of the downlink MC-CDMA system with pre-equalization is shown in Figure 34 for user k and mobile terminal j^{th} receiver. Each user k transmits $P=N_c/L$, (where N_c is the number of carriers and L the length of the spreading code) data symbols per OFDM symbol. Then the data symbols are spread into $M.L$ chips using the vector weight. The pre-equalization is performed in space and frequency before OFDM modulation and carried out jointly with spreading. Thus, each user's symbol is affected by a specific weight on each subcarrier and antenna branch.

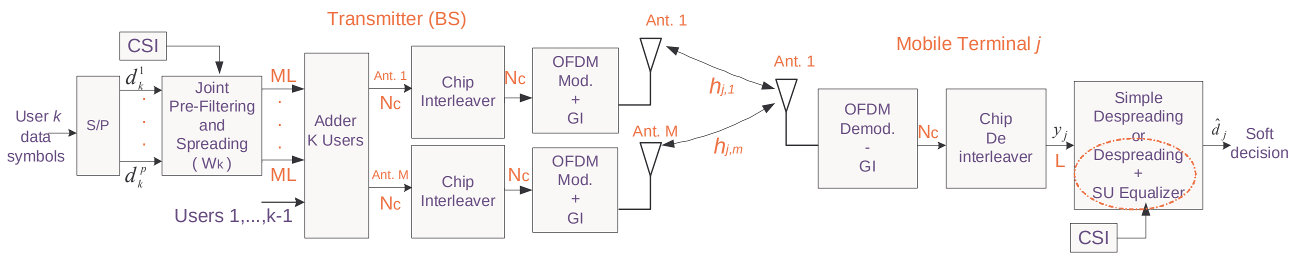


Figure 34. Downlink Space-Frequency Pre-Filtering MC-CDMA Scheme

The interference that the signal of a given user j produces at an other mobile terminal k, is given by,

$$MAI(j \to k) = \mathbf{q}_k^T \left(\sum_{m=1}^{M} H_{k,m} \mathbf{w}_{j,m} \right) \qquad \textbf{(Eq. 3)}$$

where $\mathbf{q}_k$ is a vector that depends on the code of user k and the type of receiver used, $H_{k,m}$ is the frequency domain channel vector from antenna m to mobile k and the $\{\mathbf{w}_{j,m}\}$ are the pre-equalization vectors to be optimised.

The zero-forcing criteria is therefore given by the set of linear equations

$$\begin{cases} \mathbf{q}_j^T \left(\sum_{m=1}^{M} H_{j,m} \mathbf{w}_{j,m} \right) = \alpha_j \\ \mathbf{q}_k^T \left(\sum_{m=1}^{M} H_{k,m} \mathbf{w}_{j,m} \right) = 0 \qquad \forall k \neq j \end{cases} \qquad \textbf{(Eq. 4)}$$

Different criteria can be considered for optimisation, namely;

- minimization of the total transmitted power subject to Eq. 3, i.e. $\min \sum P_k$
- minimization of the total transmitted power subject to Eq. 4 and equal power per user i.e. $P_k = P_T / K \quad \forall k$

It was observed that for coded systems where the raw bit error can be moderately high there is a noticeable difference between the two criteria, and therefore an equal power assignment leads to the simplest solution.

More complex functionals of the power assignment could be considered, like the minimization of the error probability or maximization of the sum capacity but these lead to complex optimisation problems that would require iterative numerical computations

The results of this research topic point out some interesting conclusions: if CSI is available at BS it is clearly preferable to perform space-frequency pre-filtering for MC-CDMA than frequency pre-filtering for SFBC MC-CDMA. This is due to the fact that the first scheme has both diversity and antenna gain whereas for the SFBC based scheme only diversity gain can be achieved. Comparing the pre-equalization approaches, the best strategy is to move most of the processing to the BS and perform simple despreading at the MT, which results in the simplest mobile receiver. The schemes more robust to imperfect CSI are the ones associated with the lowest complexity receivers at the mobile (like simple despreading receivers).

Simulations were carried out for the STBC with pre-filtering in scenarios with spectral efficiencies of 2, 3 and 4 bps/Hz, without channel coding and in scenarios with 1.5, 2 bps/Hz with UMTS channel turbo code, to evaluate the effectiveness of the proposed joint STBC and multi-user pre-filtering algorithm in a high data rate context.

For the SFBC with pre-filtering, simulations results were obtained for high data rate scenarios with UMTS channel turbo code.

Outcome and future actions: Dissemination in,

A. Gameiro and A. Silva, "Joint STBC and Pre-Filtering Technique for MISO TDD Downlink MC-CDMA Systems", IST Summit on Mobile and Wireless Communications 2005, Dresden, June 2005.

A. Silva and A. Gameiro, "SFBC with Pre-Filtering Technique for DL TDD MC-CDMA Systems in High Data Rate Context", IEEE Globecom 2005, Saint Louis, USA, Nov 200

A. Silva and A. Gameiro, "Transmission Strategies for MISO Downlink TDD MC-CDMA Mobile Systems” Submitted to IEEE Transactions on Vehicular Technology.

Future work in will concentrate on the use of trellis codes, and joint transmit-receive optimisation.

Activity type: ***Education and Training – Master Thesis***

Addressed research topic: **Interference Rejection at the transmitter and associated feedback**

Authors: KTH

Participants: KTH

Dates/Duration: The work was carried out from January 2004 to December 2005

Description: The scheme of [60] has been implemented on the KTH test-bed as described above in Section Two transmitters (base-stations) and two receivers (mobile-stations) were used. Elaborated use of training sequences and feedback enabled knowledge of all four 2x2 propagation channels at the base-stations (i.e. global channel knowledge). While simulation results showed minor improvements of the interference suppression, experimental results indicated large gain. A possible explanation is that the simulation results assumed independent fading in all four sub-channels of the 2x2 MIMO channels while this may have not been the case in the measurements.

The details of the scheme of [61], described briefly in Section 1.3.2, have been detailed and evaluated using the experimental data collected in the measurement campaign described in Section 6.3. Unfortunately, the results showed no improvement of the proposed scheme over a conventional scheme which used no interference suppression at the base-station. The reason for this may be that only BPSK was used and that the number of antennas at the base- and mobile-stations were the same, namely four. The gain of the proposed scheme is believed to be larger when the number of base-station antennas is much larger than the number of mobile-station antennas.

Outcome and future actions: Master Thesis,

Niklas Emanuelsson, "Experimental investigation of the use of Feedbaack in Smart Antenna Systems in Extremely Stationary Environments", Master Thesis, Royal Institute of Technology, September 2005.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Reconfigurable Transceivers with Linear Pre-coding**

Authors: Lucent

Participants: 18 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC.

Dates/Duration: 8-9 February 2005 at the internal workpackage meeting in Athens.

Description: The initial work in linear pre-coding methods for MIMO transceivers has been further developed resulting in several dissemination activities detailed below. A brief description of the main contributions is given here. The design of reconfigurable MIMO transceiver based on linear pre-coding consists in introducing a linear filter at the MIMO transmitter that allows for the utilization of certain knowledge about the channel conditions and/or properties in order to improve performance of the transmission scheme with respect of a selected performance criterion.

Linear pre-coding schemes for Space-Time Block Coded systems have been recently proposed [28][123], which achieve re-configurability to antenna correlation and Channel State Information reliability by employing a transmission scheme adaptive to channel conditions.

Recent studies have shown that high fading correlations reduce MIMO channel capacity and system performance. An optimal linear pre-coder that assumes knowledge of the transmit antenna correlations can improve the performance of a space-time coded system by forcing transmission on the nonzero eigenmodes of the transmit antenna correlation matrix. The main advantage of this pre-coder is that it does not have to track fast fading; it only tracks the slowly varying antenna correlations. These can be fed back to the transmitter using a low-rate feedback link or can be derived based on uplink channel estimation.

Let us consider a communication system that consists of M transmit and N receive antennas.

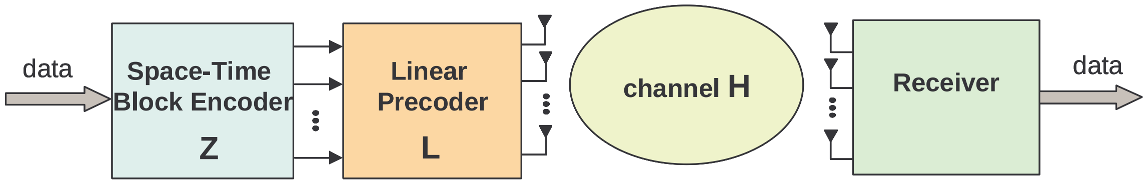


Figure 35. Reconfigurable transmission scheme combining space-time block codes and a linear transformation designed w.r.t. channel knowledge available at the transmitter

The transmitter is assumed to have some knowledge of the second-order statistics of the channel. These statistics can be obtained from the feedback bits sent by the mobile station, or they can be derived based on uplink channel estimation. As depicted in Figure 1, the space-time block encoder **Z** maps the input data sequence $\mathbf{x}=(x_1,x_2,..x_Q)$ onto an $M\times Q$ matrix **Z** of codewords that are split into M parallel sequences. These codewords are then transformed by an $M\times M$ linear transformation **L** in order to adapt the code to the available channel information. The resulting sequences, encompassed in an $M\times Q$ matrix $\mathbf{C}=\mathbf{LZ}$, are sent on the M transmit antennas during Q time intervals. Transmitted data are recovered at the receiver by means of a maximum likelihood (ML) receiver.

The signal received at the mobile is assumed to be a linear combination of several paths reflected from local scatterers, which result in uncorrelated fading across the receive antennas and therefore uncorrelated rows of matrix **H.** However, limited scattering at the base station (BS) can result in antenna correlation and, therefore, in correlated columns of matrix **H**. In such a case, as explained in [28], it is possible to use a geometry-based stochastic channel model in which the probability density function (PDF) of the geometrical location of the scatterers is prescribed. However, in the following analysis, a correlation-based channel model will be used instead for the sake of simplicity. According to the correlation-based model, the channel **H** can be written as follows:

$$\mathbf{H}=\mathbf{H}_W\mathbf{R}_T^{1/2}, \qquad \textbf{(Eq. 5)}$$

where $\mathbf{H}_W$ is an NxM independently and identically distributed (i.i.d) complex matrix and $\mathbf{R}_T$ is the $M\times M$ transmit antenna correlation matrix. The received signal **Y** is corrupted by additive white Gaussian noise denoted by the $N\times Q$ matrix $\mathbf{\Sigma}$ with covariance matrix $\sigma^2\mathbf{I}_N$:

$$\begin{aligned}\mathbf{Y} &= \mathbf{HC}+\mathbf{\Sigma}\\ &= \mathbf{HLZ}+\mathbf{\Sigma}\end{aligned} \qquad \textbf{(Eq. 6)}$$

A block-fading model in which the channel remains constant over a number of symbol periods (spanning a space-time codeword) and then changes in an independent fashion in the following realization is assumed. The antenna correlation at the transmitter and, therefore, the computed precoding matrices used to compensate for antenna correlation are assumed stationary over time.

The linear transformation **L** is determined so as to minimize a given criterion, such as an upper bound on the Pairwise Error Probability (PEP) of the codeword. The PEP is defined as the error probability of choosing in favor of the codeword $\mathbf{Z}^l$ instead of the actually transmitted codeword $\mathbf{Z}^k$.

If $\tilde{\mathbf{E}}(k,l,t)=\mathbf{Z}^k(t)-\mathbf{Z}^l(t)$ denotes the code error matrix, maximum diversity is obtained when $\tilde{\mathbf{E}}(k,l,t)$ has full rank for all k,l. The coding gain is dominated by the minimum distance code error matrix, which is defined as $\mathbf{E}=\arg\min_{\tilde{\mathbf{E}}(k,l,t)}\det\left[\tilde{\mathbf{E}}(k,l,t)\tilde{\mathbf{E}}^H(k,l,t)\right]$. It can be shown that the minimization of an upper bound on the average PEP is equivalent to the following optimization problem:

$$\begin{aligned}&\max_{\mathbf{L}}\det\left(\mathbf{I}+\frac{E_s}{\sigma^2}\mathbf{R}_T^{1/2}\mathbf{LEE}^H\mathbf{L}^H\mathbf{R}_T^{1/2H}\right)\\ &s.t: Trace(\mathbf{LL}^H)=P_0\end{aligned} \qquad \textbf{(Eq. 7)}$$

where E_s is the symbol energy and P_0 reflects a desirable power constraint.

The solution of this optimization problem is

$$\mathbf{L} = \mathbf{V_r}\mathbf{\Phi_f}\mathbf{V_e}^H$$
$$\mathbf{\Phi_f^2} = \left(\gamma\mathbf{I} - \left(\frac{E_s}{\sigma^2}\right)^{-1}\mathbf{\Lambda_r^{-2}}\mathbf{\Lambda_e^{-1}}\right)_+ \qquad \textbf{(Eq. 8)}$$

where $\mathbf{R_T^{1/2}} = \mathbf{U_r}\mathbf{\Lambda_r}\mathbf{V_r}^H$ and $\mathbf{EE}^H = \mathbf{U_e}\mathbf{\Lambda_e}\mathbf{V_e}^H$ and $\gamma > 0$ is a constant computed from the trace constraint and $(\cdot)_+$ stands for max(·,0).

When orthogonal space-time codes are considered [28], the minimum distance code error matrix is such that $\mathbf{EE}^H = \zeta\mathbf{I}$, where ζ is a scalar, $\mathbf{\Lambda_e} = \zeta\mathbf{I}$, and $\mathbf{V_e} = \mathbf{I}$. In this case the precoder becomes:

$$\mathbf{L} = \frac{1}{\sqrt{M}}\left[\ \mathbf{w}_1 \quad \mathbf{w}_2 \quad \ldots \quad \mathbf{w}_M\ \right]\begin{bmatrix} \sqrt{1+\beta_1} & 0 & 0 & \cdots & 0 \\ 0 & \sqrt{1+\beta_2} & 0 & \cdots & 0 \\ 0 & 0 & \ddots & 0 & \vdots \\ \vdots & \vdots & 0 & \ddots & 0 \\ 0 & 0 & \cdots & 0 & \sqrt{1+\beta_M} \end{bmatrix} \qquad \textbf{(Eq. 9)}$$

where $\mathbf{w}_1$, $\mathbf{w}_2$, …, $\mathbf{w}_M$ are the eigenvectors of the matrix $\mathbf{R}_T^{1/2}$, $\beta_i = \left[\left(\frac{1}{\lambda_{r,1}^2} - \frac{1}{\lambda_{r,i}^2}\right) + \cdots + \left(\frac{1}{\lambda_{r,M}^2} - \frac{1}{\lambda_{r,i}^2}\right)\right] \Big/ \left(\frac{\mathbf{E_S}}{\boldsymbol{\sigma}^2}\right)$ and $\lambda_{r,1}, \lambda_{r,2}, \ldots, \lambda_{r,M}$ are the eigenvalues (with $\lambda_{r,1} \geq \lambda_{r,2} \geq \ldots \geq \lambda_{r,M}$) of $\mathbf{R}_T^{1/2}$.

When the antenna correlation is zero, the eigenvalues of $\mathbf{R}_T^{1/2}$ are equal and, therefore, $\beta_i = 0$ and the matrix of the eigenvectors equals the identity matrix. In this case, the pre-coder becomes $\mathbf{L} = \mathbf{V_e}^H$ and is an orthogonal transformation equivalent to space-time block coding. When the antenna correlation is one, only one eigenvalue of $\mathbf{R}_T^{1/2}$ is non-zero and the pre-coder is equivalent to a beamformer.

In Figure 36 simulation results are presented for a 2×1 UMTS FDD system with spreading factor equal to 128, convolutional coding of rate 1/3 and data rate equal to 12.2 kbps. The channel correlation matrix is assumed perfectly known at the transmitter. Performance results are depicted for Alamouti space-time block coding (STTD), beamforming and the proposed re-configurable design in terms of required Eb/No for 1% FER as a function of antenna correlation. As expected STTD performance degrades when antenna correlation increases, whereas antenna correlation is beneficial for beamforming performance. The proposed scheme performs similarly to STTD for low antenna correlations and becomes equivalent to beamforming for high antenna correlation. For correlation values between the two extremes, the proposed approach outperforms both STTD and beamforming.

The sensitivity of the proposed reconfigurable design to channel state information errors at the transmitter was investigated in [29] both analytically and via simulations and its robustness was demonstrated.

The methodology of designing linear pre-coders presented in this section can be extended to non-orthogonal Space-Time Block Codes [30] and can be generalized to any form of matrix modulation, of which STBC is just a special case. Moreover, it can be applied so as to optimize criteria other that the average PEP, but it is not always possible to achieve a closed form expression for the linear pre-coding matrix and numerical methods need to be implemented.

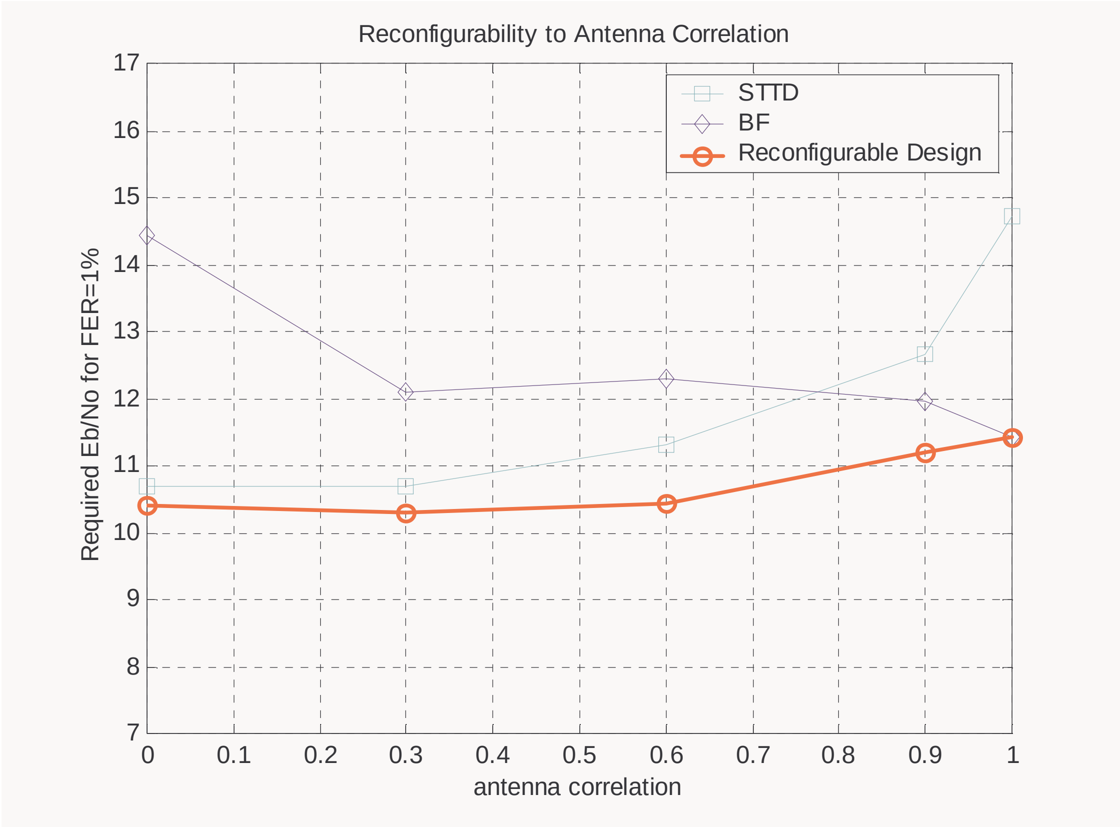


Figure 36. Re-configurability to antenna correlation

Outcome and future actions: Dissemination in,

IST-FITNESS project (http://www.ist-fitness.org)

A. Alexiou. C. Papadias, "Reconfigurable MIMO Transceivers for Next-Generation Wireless Systems", Bell Labs Technical Journal, Future Wireless Communications issue, vol. 10, No. 2, pp. 139-156, July 2005.

A.Alexiou, M. Qaddi, "Robust Linear Precoding to Compensate for Antenna Correlation in Orthogonal Space-Time Block Coded Systems", 3rd IEEE Sensor Array and Multichannel Signal Processing Workshop, July 2004.

part of this work has been contributed to WINNER project and has been disseminated in the international WWRF forum,

A. Medles, A. Alexiou. "Linear Precoding for STBC to Account for Antenna Correlation in Next Generation Broadband Systems", IEEE PIMRC 2005, Berlin, September 2005.

A. Alexiou, M. Haardt, "Smart Antenna Technologies for Future Wireless Systems: Trends and Challenges", *IEEE Communication Magazine*, vol.42, No. 9, pp. 90-97, September 2004

A. Alexiou, M. Haardt, "White paper on Smart Antenna, MIMO systems and Related Technologies", *15th WWRF Meeting*, Paris, December 2005.

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **A Class of Multi-Carrier CDMA Access Methods for Wide-Bandwidth Wireless Channels**

Authors: UPRC

Dates/Duration: The work was developed from January 1st 2004 to June 30th 2005

Description: This article describes and evaluates a general class of synchronous multi-carrier CDMA methods. In the proposed methods each accessing user is encoded by a Hadamard sequence and a multi-carrier (MC) encoder. The MC-encoder may provide one or many sub-carriers for each access channel while each accessing user may distribute its transmit power over all sub-carriers of its own access channel or over all sub-carriers of all access channels. Each sub-carrier then carries the transmitted symbols of all users which are distinguished by their Hadamard sequences. In the performance evaluation presented herein we have examined their tolerance to synchronization jitter.

Outcome and future actions: Dissemination in,

D. Gerakoulis, G. Efthymoglou, F. Koravos, L. Tassiulas, "A Class of Multi-Carrier CDMA Access Methods for Wide-Bandwidth Wireless Channels", 16th Annual IEEE International Symposium on Personal Indoor and Mobile Radio Communications, Berlin, Germany, September 2005.

Activity type: ***Dissemination activity – Journal Paper***

Addressed research topic: **Generalizations of the Golden code to more transmit antennas**

Authors: GET

Description: The schemes introduced in Section 1.3.3 can be generalized for more than two transmit antennas. The SDM can be used as it is for any number of transmit antennas as it consists in multiplexing the QAM symbols on all transmit antennas. It has always the same drawback: its low diversity gain. The Alamouti code has been generalized to orthogonal codes (with a multiplexing gain lower than one) or to pseudo-orthogonal codes (with a multiplexing gain equal to one). But, the multiplexing gain is fundamental when the number of transmit and receive antennas increases. For example, if the number of transmit antennas is equal to 4 and the number of receive antennas is at least 4, then the maximal multiplexing gain is itself equal to 4. With a full rate code (multiplexing gain equal to 4) using a 64-QAM constellation, the spectral efficiency of the system is 24 bits per channel use. Using a pseudo-orthogonal code with a multiplexing gain equal to one and for the same spectral efficiency would require a 2^{24}-QAM constellation!!

Fortunately, the Golden code can be generalized to any number of transmit antennas. These new codes are called perfect space-time block codes [68][84] and have the same properties as the Golden Code. For example, they achieve the Diversity/Multiplexing gain tradeoff and preserve the channel mutual information. Their block length is minimal (equal to the number of transmit antennas). They can be decoded in the same way as the Golden Code.

Perfect space-time block codes can be used as they are for systems using OFDM or CDMA. But they can easily be adapted to UWB MIMO systems [66] or even to FSK modulation for Bluetooth™ [70].

There has also been addressed the problem of concatenating an outer code to Space-Time codes. On such systems, generally, a convolutional code is chosen even if a LDPC code for example would be a good solution. Two main problems can be addressed. The first one is related to the binary labelling of space-time codewords, the second one is related to the soft-output decoding of the space-time code in order to implement then a soft-input decoding of the binary outer code. In UCLA (University of California at Los Angeles), some simulations have been done with the channels of IEEE 802.11n. Channel A is a non frequency selective channel whereas channels B and D are frequency selective. In channel A, the Golden code alone outperforms two schemes of the pre-standard using SDM and a binary outer code. In channels B and D, this is no more the case as the Golden code alone cannot bring the frequency diversity. This is done by the convolutional outer code.

Mapping a binary outer code to Space-Time codes is not easy to do unless we use an orthogonal Space-Time Code as the Alamouti code. In fact, we know that the best mapping to use would be a Ungerboeck mapping when the outer code is a convolutional code and a Gray mapping when the outer code is a capacity-achieving code such as a Turbo code or a LDPC code. In fact, what we know is that it is possible to do an Ungerboeck mapping of the Golden code, for the determinant criterion, in order to concatenate a convolutional code [81].

Outcome and future actions: Dissemination in,

F. Oggier, G. Rekaya, J.-C. Belfiore, and E. Viterbo, "Perfect Space Time Block Codes," IEEE Transactions on Information Theory, Sep. 2004, submitted for publication

Activity type: ***Dissemination activity – International Conference Paper***

Addressed research topic: **Classifying MIMO channels**

Authors: GET

Description: Designing adaptive modulation/coding schemes for MIMO communication systems is not an easy task. For single antenna systems, it is much easier to perform since we can choose the spectral efficiency of the coding/modulation scheme used as a quite simple function of the signal to noise ratio. When the channel exhibits a low signal to noise ratio for example, then the chosen spectral efficiency will be low. For MIMO channels, such an ordering does not exist. Moreover, the behaviour of the system also depends on many parameters and we have a new degree of freedom as we can choose the modulation, the coding, but also the space-time code depending on the true number of degrees of freedoms that the channel exhibits. For example, for channels such as keyhole channels (rank one channels), then a space-time code with multiplexing gain equal to one is optimal.

As a first step towards some solutions to that problem, we have proposed a classification of MIMO channels [78] in order then to choose some modulation/coding/space-time coding adapted to each class. By noticing that the MIMO channel matrix combined with QAM modulation can be modelled as a lattice, it has been possible to find a quantization algorithm in the space of lattices in order to put each channel realization into a class.

Outcome and future actions: Dissemination in,

J. J. Boutros, F. Kharrat and H. Randrianbololona, ``A classification of multiple antenna channels," in 43rd Allerton Conference, Sep. 2005.

Next step will be to associate to the centroids of every class a modulation/coding/space-time coding scheme.

5. Jointly Optimised MIMO Transceivers

The third main research topic addressed in the workpackage deals with antenna selection methods for multiple-input multiple-output wireless systems which has integrated the interest of UPRC and ICCS/NTUA. Both partners have established a tight collaboration producing several joint papers as detailed next in the description of the joint research activities.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Joint Optimization of MIMO Transceiver**

Authors: UPRC, ICCS/NTUA

Participants: 12 people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC; and 1 external organization: Sony Ericsson.

Dates/Duration: 11th November 2004 at the internal workpackage meeting in Nice.

Description: This technical presentation took place in the WP meeting in Nice, France, on 11th of November 2004, in the framework of JINA 2004, where ACE organized a parallel session. In this meeting, UPRC presented results on joint optimization of MIMO transceivers. The presentation included a thorough exposition of the problem of antenna selection with an emphasis on its objectives. Existing approaches and antenna selection techniques where described and categorized. Among them a novel technique, called

“Adaptive Antenna Subarray Formation” and some initial capacity results were presented, indicating the superior performance of this technique compared to traditional antenna element selection methods. Moreover, a reference to UPRC’s intentions and goals as future actions within WP-2.2.3 was made. Finally, some integration issues within ACE were addressed, showing that UPRC adopts the policy of integration among partners, which is one of the main goals of ACE, and makes it a reality.

Outcome and future actions: The presentation slides are available for downloading from the VCE server http://www.antennasvce.org/ACE/Exchange.

Activity type: ***Integrating activity- Internal workshop involving a technical presentation and discussion***

Addressed research topic: **Joint Optimization of MIMO Transceiver based on genetic algorithms**

Authors: UPRC, ICCS/NTUA

Participants: 18people representing 8 partners: CTTC, KTH, IT, Lucent, NCSRD, ICCS/NTUA, UPM, UPRC.

Dates/Duration: 8-9 February 2005 at the internal workpackage meeting in Athens-.

Description: New progress on antenna selection algorithms were presented in the framework of joint transmit and receive optimization for MIMO schemes. The presentation focused on genetic algorithm based antenna selection strategies as well as on a novel evolutionary technique, called “Antenna Subarray Formation”, which lead to MIMO systems with reduced hardware costs and enhanced instantaneous capacity. It is shown that genetic algorithm based antenna selection outperforms traditional antenna selection methods (such as Gorokhov’s algorithms) in terms of system’s capacity. Regarding antenna subarray formation, it maximizes the capacity of multiple antenna wireless systems with reduced available RF chains. It is based on the adaptive formation of subarrays with appropriate weights. The elements of each subarray and their weights are dynamically selected by an evolutionary computation technique based on the capacity cost function. After the description and mathematic formulation of the aforementioned techniques, results from their application to simulated and measured data were presented. These results included instantaneous capacity ccdf’s, enabling us to compare evolutionary methods to other “traditional” approaches and observe their superiority in terms of capacity performance.

Outcome and future actions: The presentation slides are available for downloading at http://www.antennasvce.org/ACE/Exchange.

Activity type: ***Dissemination activity – Joint journal paper***

Addressed research topic: **Selecting Array Configurations for MIMO Systems: An Evolutionary Computation Approach**

Authors: UPRC, ICCS/NTUA

Dates/Duration: Collaborative work took place from January 1st 2004 to September 30th 2004.

Description: This joint paper presents an antenna selection method for multiple-input multiple-output wireless systems. By exploitation of the channel transfer matrix, the antenna selection criterion maximizes the instantaneous capacity achieved using a specific number of transmit and receive antenna array elements. For each environment, the proposed method applies a genetic algorithm which seeks the most advantageous subset of antenna elements. The results are based on measured and simulated channels and show that the proposed method selects array configurations that yield superior performance compared to the arrays usually employed. Furthermore, comparative analysis results are presented, with respect to a state-of-the-art algorithm. For large number of antenna elements, optimal subset selection is numerically intensive, especially if an exhaustive search (ES) over all candidate subsets is to be performed. Suboptimum algorithms for single link-end antenna selection have been proposed, using the capacity criterion. The proposed method is suitable for jointly selecting transmit and receive antenna elements, assuming a system with fixed number of RF chains.

For each time snapshot t, the elements of the measured channel matrix are denoted as $G_{ij}(t,f)$, $i = 1,\ldots, M_r$, $j = 1,\ldots,M_t$, $t = 1,\ldots, T$, and $f = 1,\ldots,F$, where M_t and M_r are the number of transmitter and receiver antenna elements, respectively, T is the number of consecutive temporal snapshot of the channel matrix provided by the measuring equipment and F is the number of distinct frequency bins, occupying a total bandwidth B. All measured data are organized in a four-dimensional (4-D) matrix **G** of size $[M_r \times M_t \times T \times F]$ and are normalized as follows:

$$\mathbf{H} = \frac{\mathbf{G}}{g} = \frac{\mathbf{G}}{\sqrt{\frac{1}{M_r M_t T F}\sum_{i=1}^{M_r}\sum_{j=1}^{M_t}\sum_{t=1}^{T}\sum_{f=1}^{F}|G_{ij}(t,f)|^2}} \qquad \textbf{(Eq. 10)}$$

This normalization procedure assures that the time and frequency averaged gain of the available ($M_r \times M_t$) MIMO matrix is $M_r M_t$.

The core of the method is a genetic algorithm (GA) that seeks for the most advantageous element subset. More specifically, the proposed algorithm is a modified simple genetic algorithm (SGA) with three basic operators and a binary representation. The GA evaluates consecutive sets of candidate solutions. Each solution consists of vectors $\mathbf{T_x}$ and $\mathbf{R_x}$, which indicate the selected transmitting and receiving array elements. We define $\tilde{\mathbf{H}}$ to be a matrix that consists of the rows and columns of **H**, as determined by vectors $\mathbf{T_x}$ and $\mathbf{R_x}$. The wideband capacity achieved using the selected arrays, is then

$$C(\mathbf{Rx},\mathbf{Tx},\rho,t) = \frac{1}{B} * \int_B \log_2 \det\left[\mathbf{I}_{n_r} + \frac{\rho}{n_t}\tilde{\mathbf{H}}(\mathbf{Rx},\mathbf{Tx},t,f)\tilde{\mathbf{H}}^H(\mathbf{Rx},\mathbf{Tx},t,f)\right]df \qquad \textbf{(Eq. 11)}$$

where ρ is the average intended system signal-to-noise ratio (SNR) at each receiver antenna over the whole bandwidth. By combining the solution vectors through the crossover operator and by introducing random perturbations of the result through the mutation operator, GA aims to determine the $\mathbf{T_x}$ and $\mathbf{R_x}$ that maximize $C(Rx,Tx,\rho,t)$.

Outcome and future actions: Dissemination in a journal paper,

P. Karamalis, N. Skentos, A. Kanatas, “Selecting Array Configurations for MIMO Systems: An Evolutionary Computation Approach”, IEEE Trans. On Wireless Comms, Vol. 3, No 6, Nov. 2004.

Activity type: ***Dissemination activity – Joint International Conference Paper***

Addressed research topic: **Antenna Subarray Formation for MIMO Systems**

Authors: UPRC, ICCS/NTUA

Dates/Duration: Collaborative work took place from January 1st 2004 to December 31st 2005

Description: This joint paper studies antenna subarray formation. Assume a MIMO link occupying bandwidth B between a Base Station (BS) with fixed antenna array of M_{BS} antenna elements and a Mobile Station (MS) that employs a fixed number of M_{MS} antenna elements and N_{MS} RF chains. We focus on the downlink, where the BS acts as a transmitter and the MS as a receiver, but the analysis is applicable for the uplink also. the scope of the proposed method is to formulate N_{MS} subarrays at the MS, one for every RF chain, using all available M_{MS} antenna elements in order to maximize the MIMO capacity of the link. For each subarray, the method allocates equal number $q = \frac{M_{MS}}{N_{MS}} \in N$ of available antenna elements and chooses the complex weights to be applied to the antenna responses. All subarray elements are combined and fed to a single RF chain.

The MIMO channel is described by a 4-D time variant transfer matrix **G**, which is normalized to provide channel matrix **H**. The combined effect of the propagation channel and the receiver antenna subarrays on the transmitted signal is described by the $N_{MS} \times M_{BS}$ matrix $\tilde{\mathbf{H}}(t,f)$. At each time instant the wideband capacity is given by

$$C = \frac{1}{B}\int_B \log_2\left(\det\left[\mathbf{I}_{N_{MS}} + \frac{\rho}{M_{BS}}\tilde{\mathbf{H}}(t,f)\tilde{\mathbf{H}}^H(t,f)\right]\right)df \qquad \textbf{(Eq. 12)}$$

where ρ is the average intended system SNR at each receiver antenna over the whole bandwidth. Matrix $\tilde{\mathbf{H}}(t,f)$ is derived from $\mathbf{H}(t,f)$ by left multiplication with a transformation matrix $\mathbf{P}(t)$ with dimensions $N_{MS} \times M_{MS}$, i.e. $\tilde{\mathbf{H}}(t,f) = \mathbf{P}(t)\mathbf{H}(t,f)$. Matrix $\mathbf{P}(t)$ represents the subarray formation, since each row corresponds to a single subarray and each column to an available antenna element. The entries of **P** are given by:

$$P_{ij} = \begin{cases} w_j \text{ , if the j-th antenna element belongs to the i-th subarray} \\ 0 \text{ , otherwise} \end{cases} \qquad \textbf{(Eq. 13)}$$

where $|w_j| \leq 1$, is the complex weight applied to the j-th antenna element.

The determination of **P** that enhances capacity performance is based on a Genetic Algorithm (GA) with three basic operators and a mixed integer/floating representation. A solution consists of a vector that allocates antennas to subarrays (i.e. finds the positions of non-zero elements of the transformation matrix) and two vectors that contain the magnitude and the phase of the complex weights applied on each antenna element (i.e. define the complex weight vector $\mathbf{w}$). The GA evaluates consecutive sets of candidate solutions using instantaneous capacity C as a utility function. In the next section, it is demonstrated that the proposed GA-assisted adaptation of subarrays succeeds in converging to high-quality solutions of the aforementioned problem in MIMO channels.

Outcome and future actions: Dissemination in,

P. Karamalis, N. Skentos, A. Kanatas, “Antenna Subarray Formation for MIMO Systems”, Joint COST 273/284 Workshop on Antennas and Related Systems Aspects in Wireless Communications, Gothenburg, Sweden, June 7-10, 2004.

Activity type: ***Dissemination activity – Joint International Conference Paper***

Addressed research topic: **Adaptive Antenna Subarray Formation for MIMO Systems**

Authors: UPRC, ICCS/NTUA

Dates/Duration: Collaborative work took place September 2004 to December 31st 2005.

Description: In this paper, a new technique to maximize the capacity of multiple antenna wireless systems with reduced available RF chains is presented. The technique is based on the adaptive formation of subarrays with appropriate weights. The elements of each subarray and their weights are dynamically selected by an evolutionary computation technique based on the capacity cost function.

More specifically, the scope of the proposed method is to formulate N_{MS} subarrays at the MS, one for every RF chain, using all available M_{MS} antenna elements in order to maximize the MIMO capacity of the link. For each subarray, the method allocates equal number $q = \frac{M_{MS}}{N_{MS}} \in N$ of available antenna elements and chooses the complex weights to be applied to the antenna responses. The responses of the elements allocated to each subarray are then combined and fed to a single RF chain. The resulting MIMO system is denoted as $M_{MS}/q \times M_{BS}$, and its capacity as $C_{M_{MS}/q \times M_{BS}}$. The subarray formation procedure is repeated every T_c *(Coherence Time Period)* snapshots, allowing the system to adapt to the variations of the propagation environment. The concept of subarray formation is depicted in Figure 37.

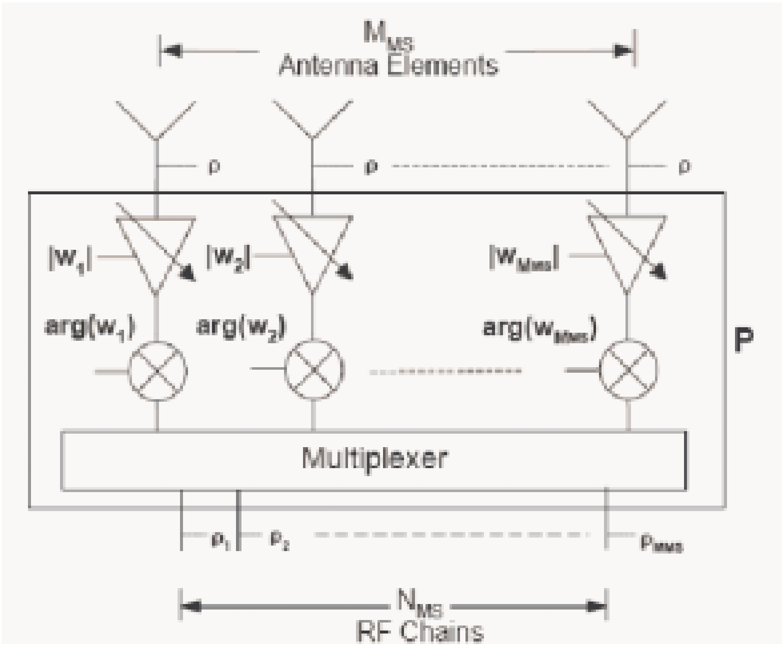


Figure 37. Subarray formation concept

As stated in the previous joint paper description, the MIMO channel is described by a 4-D time variant transfer matrix $\mathbf{T}$, which is normalized to provide channel matrix **H**. The combined effect of the propagation channel and the receiver antenna subarrays on the transmitted signal is described by the $N_{MS} \times M_{BS}$ matrix $\tilde{\mathbf{H}}(t,f)$. At each time instant the wideband capacity is given by

$$C_{M_{MS}/q \times M_{BS}}(t) = \frac{1}{B}\int_B \log_2\left(\det\left[\mathbf{I}_{N_{MS}} + \frac{\rho}{M_{BS}}\tilde{\mathbf{H}}(t,f)\tilde{\mathbf{H}}^H(t,f)\right]\right)df \qquad \textbf{(Eq. 14)}$$

where ρ is the average intended system SNR at each receiver antenna over the whole bandwidth. Matrix $\tilde{\mathbf{H}}(t,f)$ is derived from $\mathbf{H}(t,f)$ by left multiplication with a transformation matrix $\mathbf{P}(t,f)$ with dimensions $N_{MS} \times M_{MS}$, i.e. $\tilde{\mathbf{H}}(t,f) = \mathbf{P}(t,f)\mathbf{H}(t,f)$. Matrix $\mathbf{P}(t,f)$ represents the subarray formation, since each row corresponds to a single subarray and each column to an available antenna element.

In general, the subarray formation matrix is time and frequency dependent, i.e. $\mathbf{P}(t,f)$. However, the analysis henceforth is performed using narrowband channel descriptions. Thus, the subarray formation matrix is only time varying, $\mathbf{P}(t)$, and the objective is the optimization of the narrowband capacity given by the argument of the integral of (Eq. 14).

The entries of $\mathbf{P}$ are given by:

$$P_{ij} = \begin{cases} w_j \text{ , if the j-th antenna element belongs to the i-th subarray} \\ 0 \text{ , otherwise} \end{cases} \quad \textbf{(Eq. 15)}$$

where $|w_j| \leq 1$, is the complex weight applied to the j-th antenna element. In order to retain the capacity calculations to the intended system SNR measured at the output of every receiver antenna element, $\mathbf{P}$ is subject to the following normalization:

$$\mathbf{P}\mathbf{P}^H = \mathbf{I}_{N_{MS}} \quad \textbf{(Eq. 16)}$$

The determination of $\mathbf{P}$ that optimizes capacity performance is performed by a Genetic Algorithm (GA). It uses three basic operators and a mixed integer/floating representation. A solution consists of a vector that allocates elements to subarrays (i.e. finds the positions of non-zero entries of the transformation matrix) and two vectors that contain the magnitude and the phase of the complex weights applied on each antenna element (i.e. define the complex weight vector $\mathbf{w}$).

The computational effort of the exhaustive search technique is bounded by

$$\frac{\prod_{i=1}^{N_{MS}} \binom{M_{MS} - (i-1) \cdot q}{q}}{N_{MS}!} \cdot M_{BS}^3$$

complex additions/multiplications. On the other hand, the computational effort of the GA is bounded by $(G \cdot N \cdot M_{BS}^3)$ complex additions/multiplications, where G is the number of generations and N is the population size. Parameters G and N are chosen using guidelines so as to efficiently sample the search space and converge to a high fitness solution. For large search spaces, increased population size N and number of generations G is required in order to converge to the optimal solution. Therefore, the choice of GA parameters involves a trade-off between complexity, accuracy and consistency. For example, considering a typical case with $M_{MS} = 16$, $M_{BS} = 4$, $N_{MS} = 4$, $G = 120$, and $N = 60$, the ES needs $2.93 \cdot 10^{13}$ while the GA needs $4.61 \cdot 10^5$ complex additions/multiplications.

Outcome and future actions: Submitted paper to a journal,

P. Karamalis, N. Skentos, A. Kanatas, "Adaptive Antenna Subarray Formation for MIMO Systems", submitted to IEEE Trans. On Wireless Comms.

Activity type: ***Dissemination activity – International Workshop Presentation***

Addressed research topic: **Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance**

Authors: UPRC, ICCS/NTUA, KTH

Dates/Duration: Invited talk to the International Workshop organised jointly with NEWCOM Network of Excellence in the framework of the IST Mobile & Wireless Communications Summit in Dresden, 23rd June 2005.

Description: This work presents the problem of reduced hardware complexity MIMO systems and examines existing algorithms, which are candidate solutions to this problem, such as exhaustive search, Gorokhov's decremental and incremental antenna selection algorithms as well as a genetic algorithm based antenna selection algorithm. A description of two measurement campaigns, one conducted in Athens and the other conducted in Stockholm, is provided. The difference in nature between the two measurement campaigns is evident, since the first refers to Fixed Wireless Access (FWA) applications at 5.2 GHz, where there are always LOS propagation conditions and both link ends are fixed to the rooftop of buildings (rooftop-to-rooftop) or one is fixed to the rooftop and the other to the pavement at street level (rooftop-to-street), while the second refers to urban cellular applications at 1.8 GHz, where NLOS conditions dominate, the transmitter is constantly moving in the streets of the city centre at speeds that exceed 30km/h and the receiver is fixed as a base station to the rooftop of a building. The examined algorithms are applied to the available measured data and the extracted results are presented and assessed. Moreover, the novel technique of subarray formation is introduced. Results of the application of this technique to measured data are presented and used for the extraction of useful and interesting conclusions. Results mainly include capacity empirical complementary cdf's, that help us to evaluate and compare the performance of the examined MIMO transceiver optimization algorithms. Once again, one can observe the superiority of adaptive antenna subarray formation in capacity performance, for both Athens and Stockholm measurements.

Outcome and future actions:

A.G. Kanatas, K.D. Kyritsis, P.D. Karamalis, N.D. Skentos, P. Zetterberg, "Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance", Invited presentation at the Joint ACE-NEWCOM Workshop, Dresden, 23 June, 2005.

A.G. Kanatas, K.D. Kyritsis, P.D. Karamalis, N.D. Skentos, P. Zetterberg, "Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance", 14th IST Mobile & Wireless Communications Summit, Dresden, Germany, 19-23 June, 2005.

Activity type: ***Integration activity***

Addressed research topic: **Space-Time coding for the relay channel**

Authors: GET

Description: The relay channel is a simple model in order to study cooperative communication between nodes of a wireless network. We consider a wireless network with $N+1$ sources (users) and only one destination. The channels are slow fading (or delay-limited), ie, the channel coherence time is much larger than the maximum delay tolerated by the application. The channel is shared in a TDMA manner, ie, each user is allocated a time slot for the transmission of its own data. Within the same time slot, any of the other N users can help the current user transmit its information. The extension to a more general orthogonal access scheme such as OFDM or CDMA is straightforward. Suppose that the network configuration is symmetric. Without loss of generality, we consider only one time slot and the channel model becomes a single-user relay channel with one source, N relays and one destination. Here, we exclude the multi-user case, where information of more than one user can circulate at the same time in the network. All nodes in the network are supposed to be half duplex, ie, they cannot transmit and receive at the same time. The relaying protocol that was chosen is the Amplify-and-Forward strategy since it is the simplest to implement. For this protocol, it is possible to define as well as for the MIMO channel, a diversity-multiplexing gain tradeoff. This tradeoff depends on the chosen framing and is not known when terminals have multiple antennas. But what is known is that distributed versions of perfect space-time block codes achieve this tradeoff (even if we do not know it in some cases) [65][79]. For example, the distributed Golden code achieves the tradeoff for one relay and single antennas terminals. Performances of such codes on the relay channel are excellent and permit to combat for example the log-normal shadowing [65].

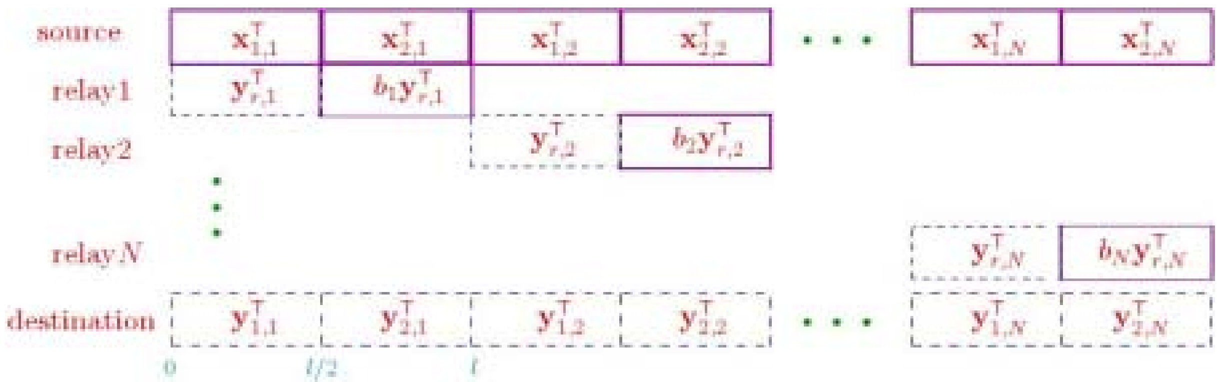


Figure 38. The best previously known framing for amplify-and-forward strategy (dashed lines represent received signals)

For *N>1* relays, then the best known framing strategy consists in relaying information with only one relay at the same time. But in that case, at low to medium signal to noise ratio, it can be shown that the cooperative strategy behaves worse than the non cooperative strategy. By optimizing the tradeoff, we found a better strategy for 2 relays which gives performance always better than the non cooperative strategy by still using a perfect space-time block code already used for the MIMO 3 transmit antennas case.

Outcome and future actions: We prepared a slides set corresponding to approximately a 3 hours talk. This slides set permits to better understand these full rate optimal space-time block codes that achieve the diversity-multiplexing gain tradeoff for the MIMO channel, but also for cooperative communication and probably for other applications. The main framework resides in algebraic number fields and cyclic division algebras. All these tools are explained in the slides set. We plan to use them as a base in order to organize a summer school in ACE 2 devoted to advanced space-time coding. Moreover, in order to disseminate these codes in the industry, we made some work on concatenating a convolutional code to these full rate space-time block codes in order to be compliant with the main MIMO wireless standards. A report is available.

6. Common tools and Measurement Data

This section relates to common tools and measurement data that have been produced in the framework of workpackage WP2.2-3 joint research activities. It includes the compilation of available software tools by participating partners, the development of a specific software tool for pre-processing of measurement data, data from measurement campaigns for several outdoor and indoor scenarios and some channel characterisation work based on available measurements.

6.1 Tools Questionnaire

This activity aimed to gather information concerning simulation and development platforms that participating partners had available and used in the framework of multiple antenna research to identify the potential level of interworking and sharing that could be expected. Of particular interest has been the available software tools and required interfaces, if needed, for exchange of data. The questionnaire also gathered the intended simulation, development, measurement and characterization plans in a time scale of two years. This activity involved providing details on the type of simulation platform (e.g. MATLAB, C/C++, …), the availability of the partner to share some modules and at which level; the kind of implementation pursued (FPGA, DSP, ASIC), and for each selected family identifying the tools used in the development cycle (simulation, synthesis, place and route, debug) and also listing the devices to be used (if already selected).

The outcome is summarize in a table available for downloading at http://www.antennasvce.org/ACE/Exchange .

6.2 Pre-processing Software Tool for Moving Scenarios

Joint work from participating partners UPRC, ICCS/NTUA and KTH lead to the development of a software pre-processing tool for later exploitation of available measurement data. The activity expanded from January to June 2005.

In order to exploit the available measurement data and use it for the development and performance evaluation of MIMO transceiver optimization techniques, an algorithm for data processing was developed, which prepares data to be appropriate for the application of MIMO transceiver optimization techniques. This procedure enables to test the validity of the Wide Sense Stationarity (WSS) assumption. Two different sets of measured data are available, one from a measurement campaign conducted in Athens, Greece, and the other from a measurement campaign conducted in Stockholm, Sweden.

The data processing procedure has been developed in Matlab environment. A block diagram depicting block functionality is shown in Figure 39. The procedure is explained more extensively next.

The available measurement data actually express the measured channel transfer function *T(t,s)*, which is time and space dependent. This is a complex valued matrix, the entries of which correspond to different time snapshots, *t*, as well as to different SISO channels, *s*. From the initial transfer function of the channel we derive the power by taking the square of the absolute value of the transfer function,

$$P(t,s) = |T(t,s)|^2 \qquad \textbf{(Eq. 17)}$$

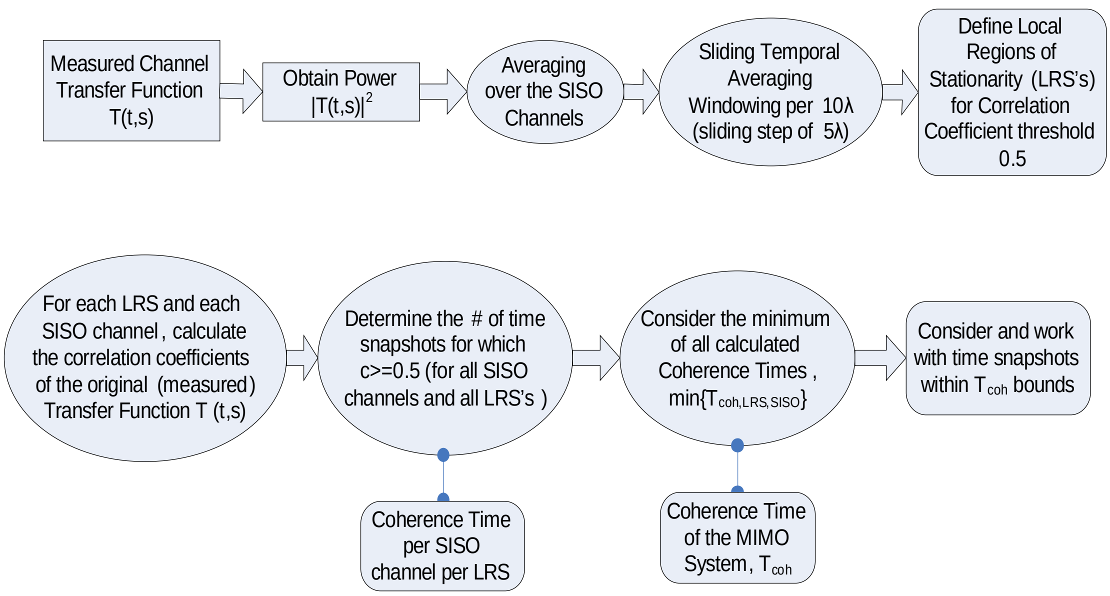


Figure 39. Stockholm Data Processing Procedure

Then we perform averaging over all SISO channels, which is mathematically expressed by the following integration:

$$P(t) = \frac{1}{S}\int_{s} |T(t,s)|^2 \, ds \qquad \textbf{(Eq. 18)}$$

In order to average out the small scale fading from *P(t)*, we perform sliding window temporal averaging. The window length is equal to the number of time snapshots corresponding to 10 wavelengths distance, covered by the moving transmitter. The sliding step of the temporal window equals the number of time snapshots corresponding to 5 wavelengths distance. This procedure produces $P(t^{'})$. Starting with $P(t_0^{'})$, where $t_0^{'}$ denotes the first sample in $t^{'}$, the correlation metric of (Eq. 19) was computed and compared to the threshold value $c_{th} = 0.5$

$$\rho_P(\Delta t_k^{'}) = \frac{Cov\left[P(t_0^{'})P(t_0^{'}+\Delta t_k^{'})\right]}{\sigma_{P(t_0^{'})}\sigma_{P(t_0^{'}+\Delta t_k^{'})}} \qquad \textbf{(Eq. 19)}$$

The interval $\Delta t^{'} = \arg\max\left\{\rho_P(\Delta t_k^{'}) \geq c_{th}\right\}$ defines the temporal length of the local regions of stationarity (LRS), which can easily be interpreted as number of initial time snapshots, if we take into consideration the sliding windowing procedure that we followed previously.

After we have detected the LRS's, we calculate the correlation coefficient matrix of the original (measured) channel transfer function *T(t,s)*, for each LRS and each SISO channel. Then, we can determine the number of time snapshots for which correlation coefficients exceed the threshold of 0.5 ($c \geq 0.5$), for all SISO channels and all LRS's. In this way, we have detected Coherence Time per SISO channel per LRS, $T_{coh,LRS,SISO}$. In order to find the coherence time of the whole MIMO system, $T_{coh,MIMO}$, we consider the minimum value of all calculated coherence times:

$$T_{coh,MIMO} = \min\left\{T_{coh,LRS,SISO}\right\} \qquad \textbf{(Eq. 20)}$$

Now that we have detected the coherence time of the MIMO channel, we are able to choose an appropriate data sampling rate, so that the sampling period is shorter than the coherence time of the channel. In this way, the measurement data, which will be subsequently used for our MIMO transceiver optimization techniques, contain consecutive time snapshots, the temporal distance of which is smaller than $T_{coh,MIMO}$.

The data pre-processing algorithm determines the appropriate data sampling rate that should be used for our measured data, when applying MIMO transceiver optimization techniques. It is very important since it makes the later extracted results suitable for reliable assessment and conclusions. Therefore the developed software tool can always be used as a data pre-processing step, when using measurement data. Matlab source file is available under request to the any of the involved partners.

6.3 Measurement campaigns

As a result of ACE WP2.2-3 activity, outdoor measurement campaigns have been conducted in July 2004 and September 2005 jointly by KTH and UPM.

In both these campaigns the simultaneous MIMO channels between one mobile station (MS) and two base-stations (BS) have been measured. This makes is possible to analyze cross-correlation properties between the links to the two base-station and also to perform multi-cell simulations directly on the measurements. The outdoor campaigns have been performed under urban macro-cell conditions.

Figure 40 below shows results from the campaign of July 2004. In the figure the positions where the same MS antenna (among four) is the strongest to both base-stations (Vanadis and Kårhuset) is marked with green while the positions when they are different are marked with red. The results from the campaign showed generally that the links of the two base-stations were generally uncorrelated in all senses [55][57]. These measurements were also used in the paper [58].

In Figure 41 the mobile trajectory in the outdoor measurements of September 2005 is shown. Two two-antenna base stations transmitted data simultaneously that was received at a mobile station equipped with one 4 antenna ULA and one 4 antenna box-structure array (the latter the same MS antenna as used in the July 2004 campaign). The two BS antennas were mounted on opposite corners of the same building some 60 meters apart (and pointing in the same directrion), giving them almost identical surrounding environment. This data has not been analyzed yet. In this case there is likely to be some correlation due to the proximity of the two base-stations.

Outdoor-to-indoor measurements have been performed in July 2004 and August 2005. In the July 2004 campaign the measurements were made with the same base-station locations as in the outdoor campaign of the same date. This has enabled a comparison of outdoor-to-outdoor and outdoor-to-indoor results. The results were found to be similar in terms of angle-spread at the BS and MS [39].

Indoor measurement campaigns were made in August of 2005 to compare two multiple antenna structures. In addition to this, measurements were also done with two base stations simultaneously so that the joint properties of multiple links between one mobile-station to a mobile-station can also be studied (as in the outdoor data above). The data has not been analyzed yet. Figure 42 below illustrates the floor plan where also the position of the base-station antennas has been indicated. The different combinations of base-station antenna positions used during the measurements are given in Table 3.

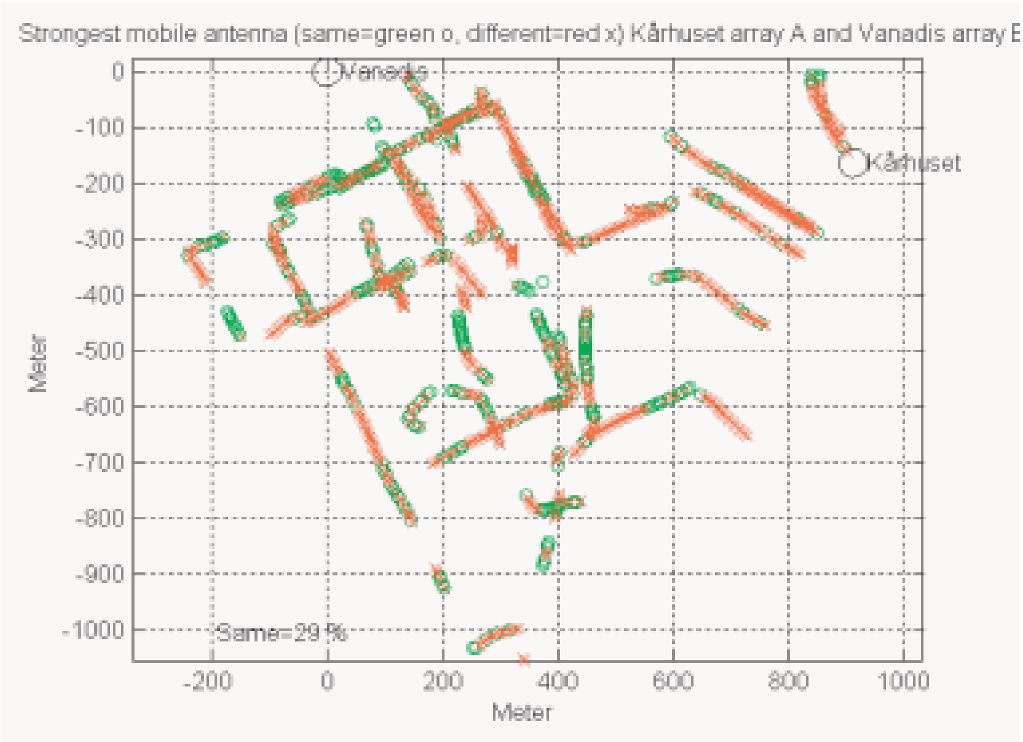


Figure 40. Illustration of where the same MS antenna is the strongest in sector A and B (which are on different sites).

The measurements were done in downlink where 2 two-antenna BS transmitted signals simultaneously that was received my one MS equipped with 2 4-antenna arrays. One 4 element ULA used as reference antenna and the second antenna was a 4 element patch antenna, which also was the antenna configuration under study. The setup of the two BSs is divided in 4 configurations which can be described as in the table below. For these measurements some basic analysis has been started that has confirmed previous results found in the literature regarding e.g. the distribution of the channel coefficients.

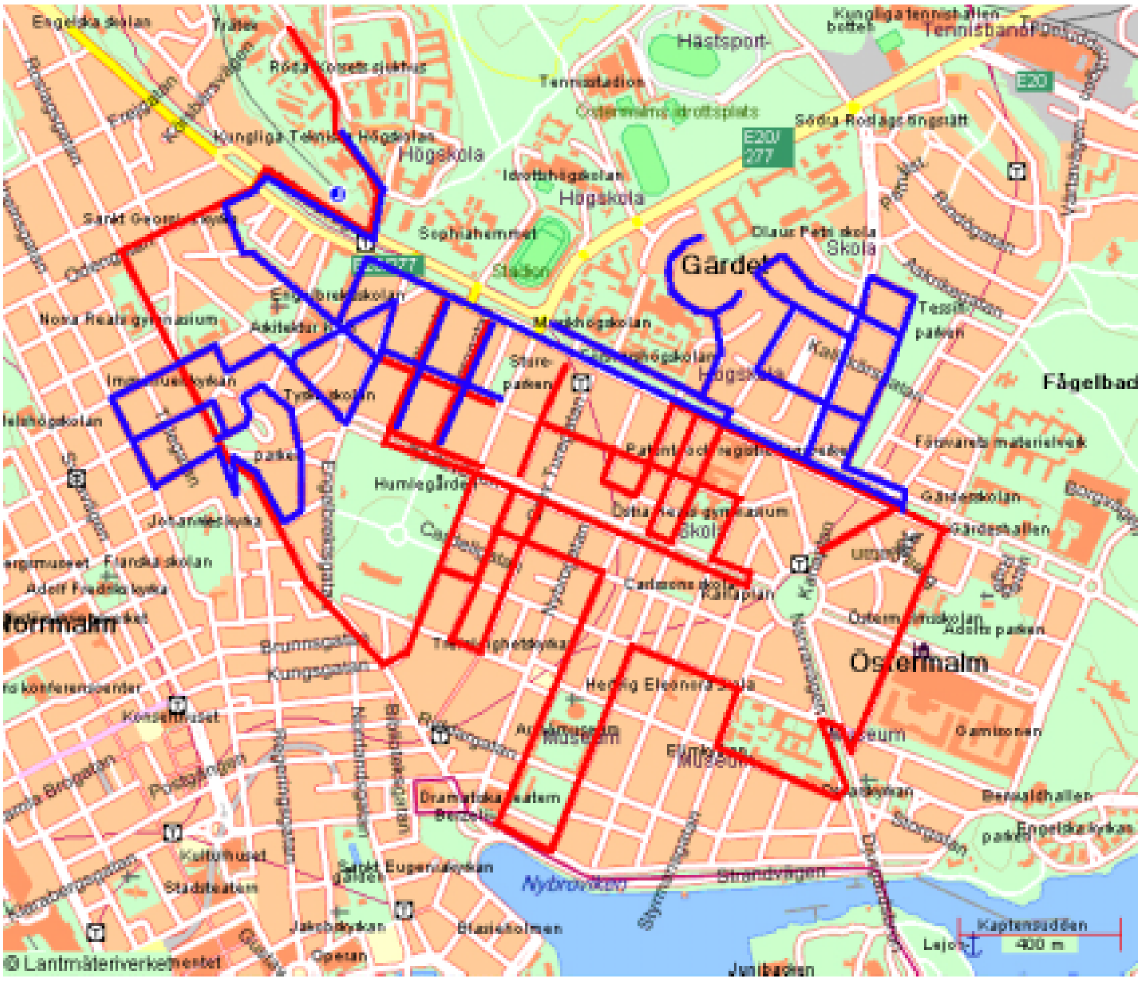


Figure 41: Illustration of measured trajectory in the September 2005 measurements.

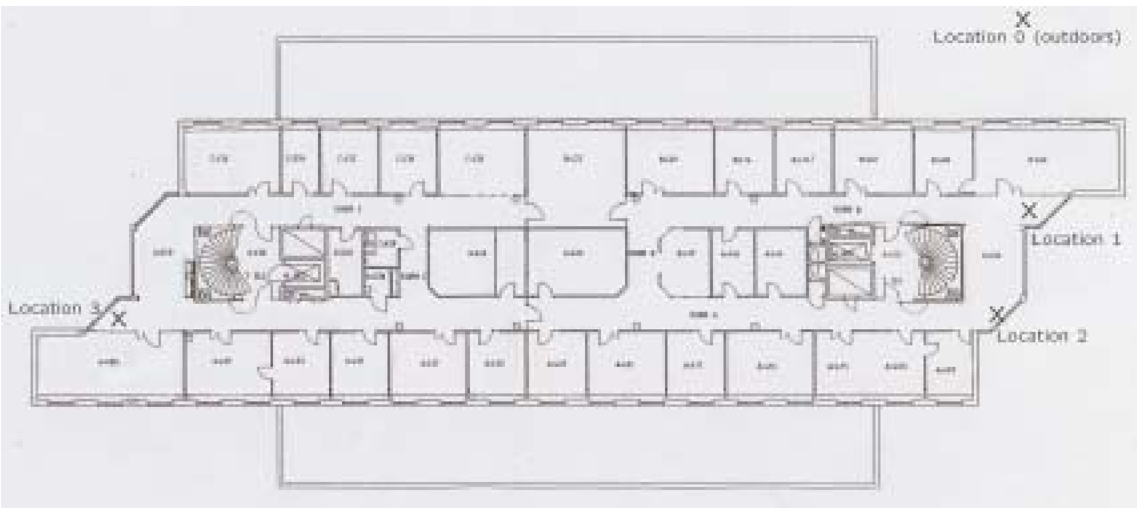


Figure 42: Floor plan during the indoor measurements.

Table 3: Position of the BS antennas corresponding to the four different setups used.

BS	Setup 1	Setup 2	Setup 3	Setup 4
1	1	0	1	1
2	1	0	3	2

The antenna locations can be seen in the floor plan picture. Location 0 is an outside position roughly entered in the picture. In all the indoor setups the antennas pointed in the corridor directions to give as good coverage as possible.

All corridors were measured twice, one in each direction, as well as some of the rooms, for each of the setups. Further more, for each setup, the antennas was placed on the same floor and measurements were done by moving the MS on the same floor and one below and one above. The above floor has an identical floor plan, whereas the floor below id a bit different with larger rooms and slightly shorter corridors.

Specific outcome from this activity comprises two international conference papers, one presentation at the General Assembly of URSI and some of the data were used in an invited presentation at the ACE-NEWCOM workshop in the IST Mobile and Wireless Communications Summit,

Per Zetterberg, Niklas Jaldén and Mats Bengtsson, "Analysis of Multi-Cell {MIMO} Measurements in an Urban Macrocell Environment", General Assembly of Internation Union of Radio Science (URSI), oct, 2005.

Per Zetterberg, Niklas Jaldén, "Comparison of Angle-Spread in Outdoor-to-Outdoor and Outdoor-to-Indoor Cases in an Urban Macro-Cell", Wireless Personal Multimedia Communications WPMC, 2005, sep, Aalborg.

Per Zetterberg , Niklas Jaldén, Kai Yu and Mats Bengtsson, "Analysis of {MIMO} Multi-Cell Correlations and Other Propagation Issues Based on Urban Measurements", IST Mobile and Wireless Communications Summit, 2005, mar.

Athanasios Kanatas, Konstantinos Kyritsis, Panagiotis Karamalis, Nikolaos Skentos and Per Zetterberg, "Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance", IST Mobile and Wireless Communications Summit, ACE-NEWCOM Session, 2005.

The close collaboration in ACE between KTH and UPM resulted in the internship from June to October 2005 of the PhD candidate Laura Garcia to KTH premises, where she work on the design of a reference antenna ray in collaboration with task 5 and contribute to the measurement campaign that was carried out at KTH .

Future actions will concentrate on analyzing the data.

6.4 Preliminary measurements with the UPM MIMO test-bed

Using the MIMO test-bed developed by UPM that has been described previously some initial measurements were performed, whose preliminary results are summarized next.

An indoor office-like scenario has been considered for all the measurements. More specifically, the measurement campaign was carried out in 2 multi-rooms with several desks and computers, and 1 laboratory containing different measurement equipment, in the School of Telecommunication building, UPM. Some of the measurements were performed in a static scenario, that is, transmitter and receiver were kept in fixed positions and the environment did not change during the measurement, and some others were obtained while moving the receiver with a pedestrian speed (around 1 m/s). Note that for all the measurements the transmitter module is kept in the same position. Line-of-sight (LoS) and Non-line-of-sight (NLoS) scenarios are considered.

In order to generate a fading channel by moving one of the modules, the multi-antenna receiver was mounted on a cart. Figure 43 depicts the MIMO test-bed (transmitter and receiver) in the laboratory room for a fixed measurement, while Figure 44 shows the moving receiver side in one of the multi-rooms.

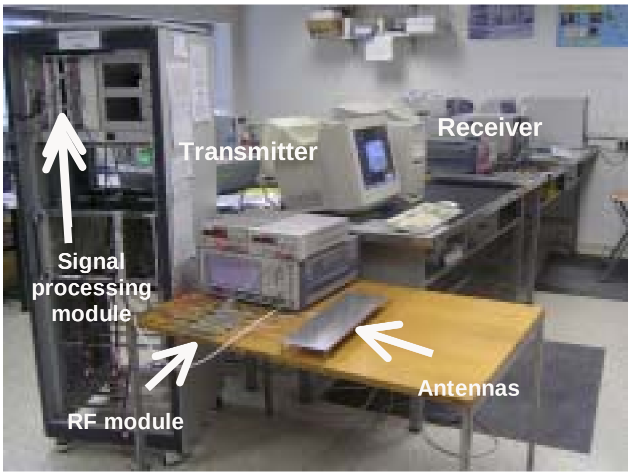


Figure 43. Test-bed in laboratory scenario

Figure 44. MIMO Receiver, office scenario

Three initial positions were considered for the receiver module, which are referred as "LOS", "NLOS1" and "NLOS2". Figure 45 shows the building plan of the office environment were the measurements took place.

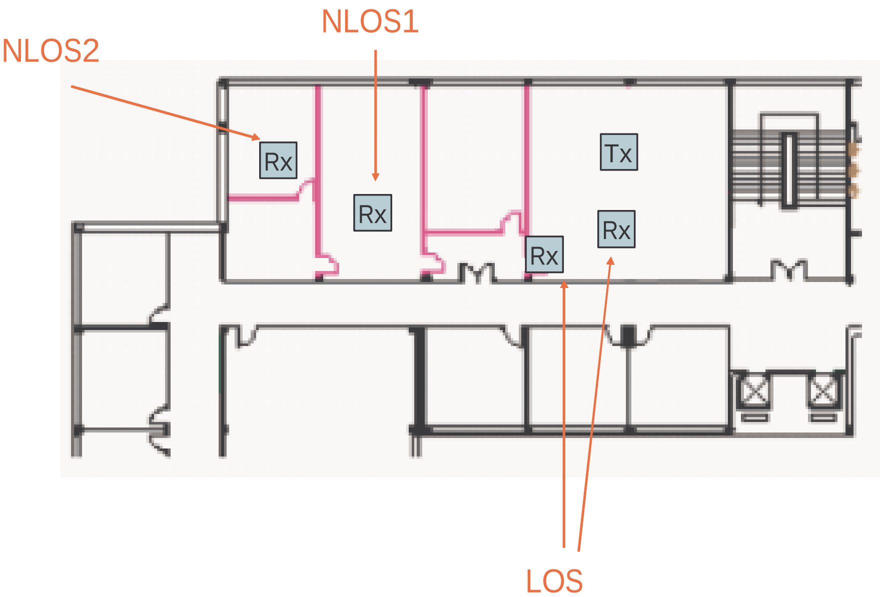


Figure 45. Building plan were measurements were done.

In order to get complete and fully accurate results, an exhaustive measurement campaign is required, so enough data are obtained and a proper statistical analysis of the data is possible. Given the available time resources this deliverable contains only some initial tests and measurements aiming at validating the test-bed performance and obtaining initial results. More exhaustive measurements are currently being carried out and will be part of ACE2 activities.

In these preliminary results the focus has been on the estimation the channel matrix. The first parameter that may be evaluated from the test-bed, in order to validate its performance, is the estimated channel matrix **H** from the collected data. The element $h_{i,j}\ (t,\tau)$ represents the normalized channel matrix response from transmitter *j* to receiver *i*, as a function of time and delay. The time axis depicts module (“power”) variations in the channel during the measurement, such as fading variations, while the delay axis shows the power-delay profile, that is, the possible multipaths. Next figures show h_{11} for two very different cases:

- a measurement in a fixed or static scenario
- and one with the receiver in motion.

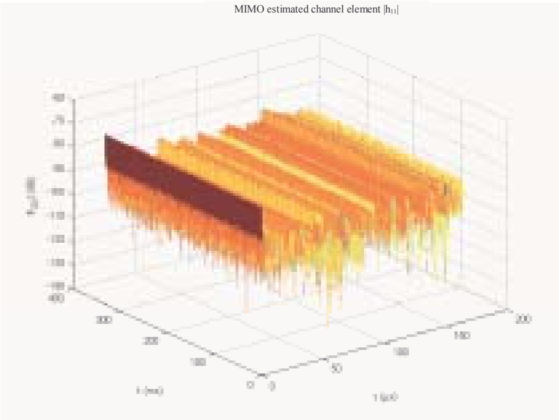


Figure 46. $|h_{11}|$, static measurement

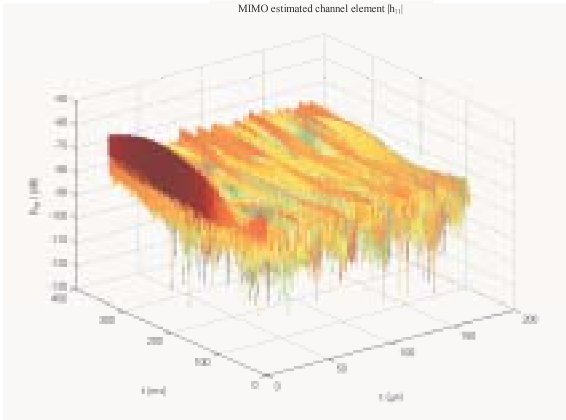


Figure 47. $|h_{11}|$, measurement in motion

As expected, the main difference between both measurements is the observed fading. While in Figure 46 (static measurement) the module of the estimated **H** matrix is constant along the whole measurement, a deep fading behaviour appears in Figure 47 (measurement with movement), which is a reasonable and expected behaviour. Note that a calibration process has been carried out, so the depicted **H** matrices are not normalized to their maximum value, but to the transmitted power.

Although an exhaustive measurement campaign was not able to be performed, a rough study of the obtained capacity and its cumulative distribution function (cdf) was done for several cases of interest. Here we summarize the most interesting ones, leaving for future work a more thorough study.

First, the available capacity has been evaluated for several MIMO configurations with different number of transmit and receive antennas. An SNR of 20 dB and no channel state information available at the transmitter was considered. The cdf functions for a MIMO system with equal number of transmit and receive antennas $N \times N$ antennas, for N=1,2,3,4 is depicted in Figure 48. The obtained values compared to theoretical results for an i.i.d. channel are in good agreement. Note that due to the not large enough available data set, the cdf slopes are steep.

Also two different element spacing were evaluated, for the LOS case, d = λ and d = λ/2 which resulting cdf capacity are depicted in Figure 49.

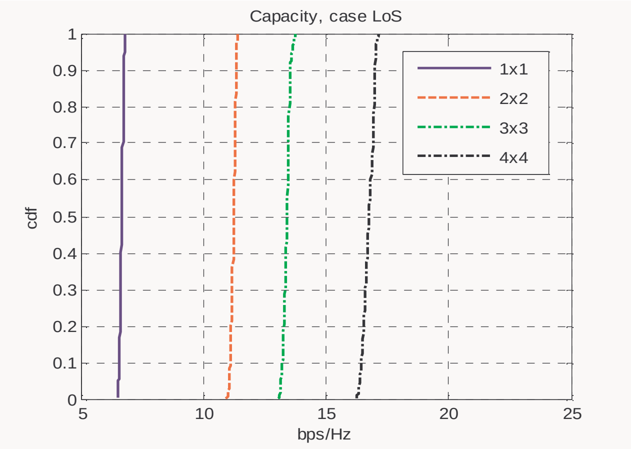


Figure 48. Capacity comparison as a function of number of antennas.

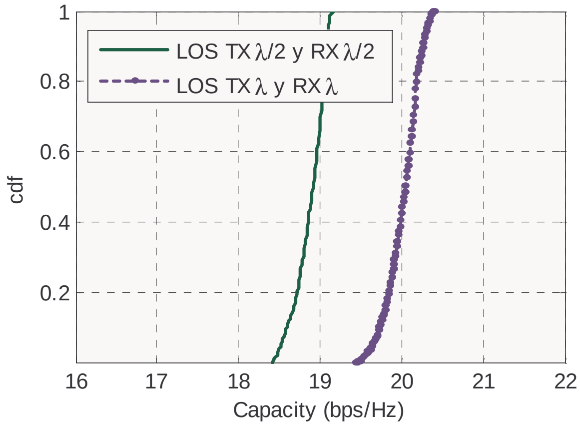


Figure 49. Capacity comparison as a function of elements spacing.

The results show that for closer elements the available capacity in the 4×4 MIMO channel decreases, since the coupling coefficients increase, thus reducing the theoretical diversity in the channel.

Finally, three different initial positions for the receiver are evaluated with the corresponding results being shown in Figure 50. As expected, the capacity is higher for non-line of sight measurements, since the correlation among antennas is smaller and therefore the diversity increases. The case “NLoS1” appears to be the best one, regarding capacity. This is a reasonable result, because the office where the receiver was located in this case contains many scatterers and thus a higher diversity performance is shown.

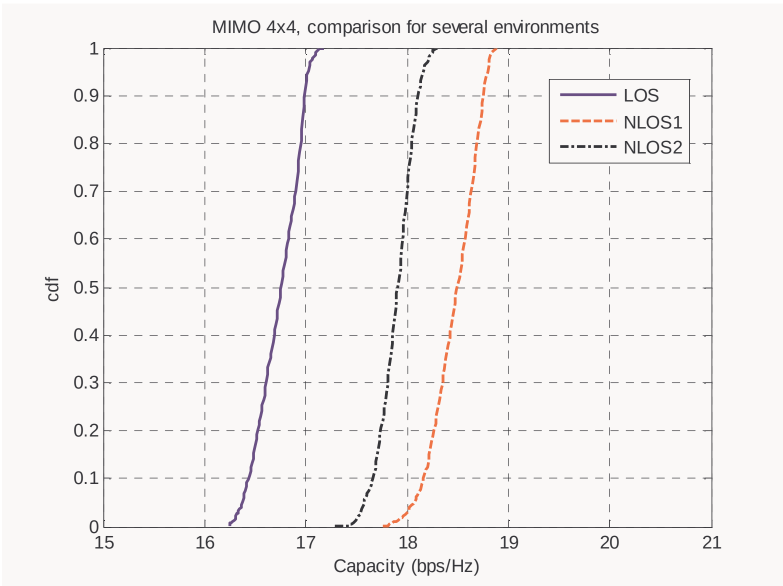


Figure 50. Capacity comparison as a function of scenario.

The implemented MIMO test-bed has allow us to present the above results as an initial outcome of the test-bed facilities. On-going measurements are expected to validate the results above, as well as include deeper analysis and evaluations.

6.5 MIMO Channel Characterization

UPRC and ICCS/NTUA carried out joint work on MIMO channel characterization from available short range rooftop to rooftop wideband measurements, with the outcome on the following joint paper

> N.D. Skentos, A.G. Kanatas, and P. Constantinou, "MIMO Channel Characterization Results from Short Range Rooftop to Rooftop Wideband Measurements", IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, WiMob 2005, Montreal, Canada, 22-24 August 2005.

This paper presents results from fixed outdoor wideband multiple input multiple output (MIMO) channel measurements performed at 5.2 GHz. Rooftop to rooftop, short range environments, under line of sight (LoS) propagation conditions were examined using 8-element vertically polarized uniform linear arrays. The scope of the work was to provide MIMO channel characterization results that could be used for either stochastic or physical channel description. In particular, delay dispersion measures, Doppler spectrum, Rice factor and spatial fading correlation results are reported. Furthermore, with the use of a two dimensional parameter estimation algorithm, multipath components' parameters are extracted and indicative double directional power spectra are provided.

A typical characteristic of the measured channels is their slow time variance, described by a narrow peaky Doppler spectrum. The shape of the latter was approximated and an empirical formula was provided. Also, based on the narrowband channel impulse response, Rice factor and spatial fading correlation results were reported. The fading signals in the arrays placed at the rooftop decorrelate very slowly with the element distance suggesting the use of cross polarized antennas. Additionally, the results of a two dimensional parameter estimation algorithm allowed the assessment of the Multipath Components (MPCs') characteristics. In particular, it was shown that the number of MPCs detected decreases as the transmitter-receiver separation distance increases. At the measured location where the largest N MPCs were detected, it was found that $N \leq 40$ 90% of time. Regarding the angular dispersion that is introduced by the propagation medium, plots of the double directional power spectra were provided indicating the clustered nature of the MPCs.

7. Education, Training and Dissemination Activities

This section relates to the activities that have directly or indirectly resulted from the research activities performed in workpackage WP2.2-3.

- **MIMO Communication Systems and Antennas Short Course part of the European School of Antennas**

This course was organized by KTH and as a result of the joint research activities of WP2.2-3 and WP2.2-4 CTTC participated in the execution of the course addressing cross-layer aspects in MIMO systems, as part of the lecturing program. The course involved 15 teachers and assistants (KTH (organizer), Ericsson AB, HUT, CTTC) and had the participation of 19 students from (Chalmers, CTTC, Ericsson, FTR, HUT, UNIFI, UPM, UNIBHAM, Univ. of Krakow, Sistemas Radiantes). The course dealt with MIMO communication systems in terms of signal processing and resource allocation and antennas for such systems, in particular small antennas for MIMO terminals The course consisted of three parts, computer based antenna-design and evaluation, signal processing laboratory on a real MIMO test-bed, and talks on signal-processing and resource allocation in multi-user MIMO systems.

The signal processing laboratory was done on the real-time multi-user MIMO test-bed (MUMS) of KTH. This was a hands-on lab on MUMS which consists of radio hardware and antennas, DSP boards and host PCs in addition to the software. The hardware has imperfections such as frequency offsets and inter-symbol interference, and a larger part of the effort is overcoming those limitations. The lab also illustrates the use of feedback, channel tracking, channel coding and adaptive modulation. In addition, the benefits of MIMO over SISO are demonstrated.

In another part of the course the students worked with MUMS offline. The students modified software that implements a single-stream MIMO approach (single-stream as opposed to multi-stream which is used in spatial multiplexing or BLAST type schemes), in which the systems performs beam-forming at the transmitter and receiver. An important aspect of this is the channel estimation at the receiver and the feedback. The students need to inserted small pieces of code in the channel estimation, and transmitter and receiver beamforming. Issues like beam-former update rate were also addressed.

The antenna-design part of the course provided a brief overview of design principles for small antennas for mobile communications systems. This included the theoretical background, design principles, implementation aspects, and measurement methods for wideband multi-element (especially MIMO) terminal antennas. The students designed antennas with modern SW tools and assessed their efficiency, MEG, and realistic MIMO performance with computational methods.

Several talks on signal processing and resource allocation in MIMO systems were given. Some of more tutorial background style, and some on more advanced and novel schemes such as multi-user scheduling and linear pre-coding.

The course had a very positive review from the students and will be given in and updated version in 2007, as part of ACE2 activities.

- **Antennas for User Terminals: Small Antennas**

UPM gave part of the lectures in the Short Course part of the European School of Antennas that took place on the 14-17 September 2005, Gandia (Spain)

- **Master Thesis on design, implementation on a software-radio platform and measurements of a MIMO test-bed for wireless communications.**

Part of the work of Carlos Gómez (UPM) Master Thesis has contributed to the development and implementation of the UPM MIMO test-bed.

- **Presentation of ACE activities in the framework of a joint PhD program between University of Aveiro and University of Porto**

ACE research activities related to signal processing aspects of multiple antenna systems represented by WP2.2-3 and WP2.2-4 where presented and disseminated in the framework of a joint PhD program between the Instituto de Telecomunicações (University of Aveiro) and the University of Porto. A brief presentation was made by A. Gameiro concerning the activities of ACE, in order to point out the research issues that are currently considered relevant in the filed of antennas. This is to be considered as an input for the definition of the PhD programme which is currently under preparation.

- **Joint Seminar ENST (GET-Telecom Paris)/ KTH at Stockholm**

The joint seminar took place in Stockholm, 26-27 January, 2005. The purpose was, on the first hand, that the two people of ENST (Jean-Claude Belfiore and Ghaya Rekaya) presented the work of ENST on optimal algebraic space-time codes that achieve the Diversity Multiplexing gain tradeoff and, on the second hand that people from Prof. Bjorn Ottersten’s department present their work on space-time coding, especially when partial feedback is available at the transmitter end and some results on sphere decoder complexity.

Slides of the presentations are available for downloading at http://www.comelec.enst.fr/~belfiore.

- **Organization of ACE-NEWCOM workshop at the IST Mobile & Wireless Communications Summit on Smart Antennas**

Workpackage WP2.2-3 participated in the organization and execution of the workshop "Smart Antennas, MIMO and Multiuser Systems" in the framework of the IST Mobile & Wireless Communications Summit, jointly with the NEWCOM Network of Excellence, on June 23, 2005. The theme of the workshop included topics on smart antennas, multiuser communications and MIMO systems and consisted of the following invited presentations:

  - **Prof. Miguel Ángel Lagunas**: Flexible MIMO Architectures: Guidelines in the Design of MIMO Parameters
  - **Prof. Shlomo Shamai**: MIMO broadcast channel capacity
  - **Pr. Robert Fischer**: Precoding techniques for the MIMO broadcast channel
  - **Prof. David Gesbert**: Scheduling and multiple antennas, a cross-layer design
  - **Prof. Raymond Knopp**: Multiuser diversity and fairness in delay-limited wireless cellular networks
  - **Dr. Panagiotis Karamalis**: Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance
  - **Prof. Atilio Gameiro**: Scheduling and multiuser diversity
  - **Prof. Panagiotis Demestichas**: Design of context-aware, reconfigurable, high-speed wireless access systems

Presentation by Prof. Lagunas and Dr. Karamalis were a direct contribution from WP2.2-3. The former presented state-of-the-art results on flexible MIMO architectures, where flexibility is presented closely related to the available channel state information. The presentation addressed interesting aspects such as the role of LOS in full CSI and no-CSI systems, the impact of the SNR at the receiver and the impact of CSI in adaptive modulation for MIMO channels. The later presented recent work on antenna selection performance evaluation for two different channel measurements campaigns performed by the involved partners. The proposed antenna subarray selection algorithm has shown to allow to reduce transceiver complexity by decreasing the number of required RF chains and as well as has successfully adapted to the propagation environment..

The workshop attracted a great amount of attention both within the ACE and the IST community and the international research community, with attendees from Europe, Asia and America. It was the most attended workshop of the IST Summit with over 40 registrations. The workshop received many positive comments from the IST and the international research community and numerous requests for access to the material of the presentations.

More details and the presentation files can be found on the workshop's website (http://mobilesummit2005.org/session.php?session=102)

- **Presentation at the PIMRC 20005 by a member of the Scientific Council**

At the PIMRC 2005, Berlin, the member of the Scientific Council, Jack Winters (Motia Inc), gave a plenary lecture on Smart Antennas: "Smart Antenna Techniques and Application to Ad Hoc Networks" and provided informal feedback on the Network activities in relation to the Smart Antennas and Multiple Antennas aspects.

8. Conclusion

We have reviewed the state of the art on MIMO transceivers and presented the identified research gaps, partially of which have been covered by the partners research work during the two years expand of the project. Considerable progress has been made towards integrating expertises on MIMO test-bed development which has resulted in both new prototypes and new implementations on the existing prototypes allowing for algorithm testing. Test-beds have also provided the means for new measurement campaigns and have served as the basis for collaboration and training purposes. The initial know-how for ACE2 in that respect shall take the work plan to an advantageous starting point.

The technical work carried out in the Activity dedicated to Smart Antennas and MIMO systems for mobile communications has been extensively disseminated in ACE organised workshops and special sessions, a part from dissemination in traditional conferences.

Capacity-achieving MIMO architectures for partial channel state information at the transmitter have been studied and scalable approaches, where optimum transmission strategy selected according to the available CSI have been proposed. Leveraging on this expertise, we intend to continue the work on the design of algorithms that optimize resources depending on channel conditions and training sequence length in phase2, incorporating channel coding aspects in the analysis of the different MIMO architectures in order to evaluate the relative gains. Future work in the line of the research topics addressed during phase I will continue to pursue the ultimate goal of optimising the design of re-configurable communication systems at both the transmitter and receiver side.

References by members of ACE

[1] P. Marques, Y. Yi and A. Gameiro, "Performance Evaluation of Channel Estimation Techniques for a beyond 3G Systems", MWCN2005, Marrakech, Morocco, Sept. 2005.

[2] P. Marques, A. Pereira and A. Gameiro, "Pilot and data aided channel estimation for uplink MC-CDMA mobile systems", IST SUMMIT 2005, Dresden, Germany, June 2005

[3] A. Silva and A. Gameiro, "Joint STBC and Pre-Filtering Technique for MISO TDD Downlink MC-CDMA Systems", IST SUMMIT 2005, Dresden, Germany, June 2005

[4] A. Silva and A. Gameiro, "SFBC with Pre-Filtering Technique for DL TDD MC-CDMA Systems in High Data Rate Context", IEEE Globecom 2005, Saint Louis, USA, Nov 2005

[5] A. Silva and A. Gameiro, " Transmission Strategies for MISO Downlink TDD MC-CDMA Mobile Systems" Submitted to IEEE Trans VT

[6] A. Silva and A. Gameiro, "Joint STBC and Pre-Filtering Technique for MISO TDD Downlink MC-CDMA Systems", IST SUMMIT 2005, Dresden, Germany, June 2005

[7] J. Bastos and A. Gameiro, "Multisensor Interference Cancellation Performance in Asynchronous Uplink on MC-CDMA Systems", Asian Pacific Conference on Communications, APCC2005,Perth Australia, Oct 2005

[8] A. Gujaria, J. Bastos and A. Gameiro, "Performance of Equalization Schemes for Extended Space-Time Coding Techniques", submitted to ICT 2006

[9] L. Gonçalves and A. Gameiro, "Multi-Sensor Frequency Domain Multiple Access Interference Canceller for DS-CDMA Systems ", Accepted for publication at the European Trans Telec

[10] F. Rubio, X. Mestre, "Semi-blind ML channel estimation for MC-CDMA systems with code-multiplexed pilots", VI IEEE Workshop on Signal Processing Advances in Wireless Communications, New York (USA) June.

[11] P. Marques and A. Gameiro, "Low-complexity Channel Estimation for Beyond 3G Systems", VTC Fall, Los Angeles, Sept. 2004.

[12] P. Marques and A. Gameiro, "Uplink MIMO Channel Estimation for Beyond 3G Systems", Fifth IEE International Conference on 3G Mobile Communication Technologies, London, UK, Oct 2004.

[13] P. Marques, Y. Yi and A. Gameiro, "Performance Evaluation of Channel Estimation Techniques for a beyond 3G Systems", IEEE MCWN 2005, Morocco, Sept 2005.

[14] C. Ibars and S. Pfletschinger, "Iterative Multiuser Receiver for Multi-resolution Broadcasting," Proc. 38th Asilomar conference on Signals, Systems and Computers, Pacific Grove, CA, Nov. 2004.

[15] C. Ibars, M. Tan and Y. Bar-Ness, "Equal SNR Power Distribution for Generalized DFE Structures," Proc. Wireless Communications and Networking Conference (WPMC), Abano Terme, Italy, Sept. 2004.

[16] L. Gonçalves and A. Gameiro, "Multi-Sensor Frequency Domain Multiple Access Interference Canceller for", Accepted for publication at the European Trans Telec.

[17] D. Gerakoulis, G. Efthymoglou, F. Koravos, L. Tassiulas, "A Class of Multi-Carrier CDMA Access Methods for Wide-Bandwidth Wireless Channels", 16th Annual IEEE International Symposium on Personal Indoor and Mobile Radio Communications, Berlin, Germany, September 2005.

[18] A. Qatawneh, L. de Haro Ariet , OFDM-MIMO system using Cayley differential unitary space time coding, Sensor Array and Multichannel Signal Processing Workshop, SAM 2004, 18-21 July 2004, Sitges (Spain).

[19] N. Manuelsson, "Experimental investigation of the use of Feedbaack in Smart Antenna Systems in Extremely Stationary Environments", Master Thesis, Royal Institute of Technology, September 2005.

[20] M. Navarro, and A. Grant, "Beamforming with Imperfect Channel Knowledge: Performance Degradation Analysis based on Perturbation Theory," in Proc. IEEE Sensor Array Workshop (SAM'04), Sitges, Barcelona (Spain), July 2004.

[21] M. Payaró, X. Mestre, and M. A. Lagunas, "Optimum Transmit Architecture of a MIMO System under Modulus Channel Knowledge at the Transmitter," in Proc. IEEE Information Theory Workshop (ITW'04), San Antonio, TX (USA), October 2004. ISBN 0-7803-8721-X.

[22] M. Payaró, X. Mestre, A.I. Pérez-Neira, and M. A. Lagunas, "On Power Allocation under Phase Uncertainty in MIMO Systems," in Proc. Winterschool on Coding and Information Theory. Bratislava, Slovakia. February 20-25, 2005. ISBN 3-902477-01-6.

[23] F. Rubio, X. Mestre, "Asymptotic performance of code-reference spatial filters for multicode DS/CDMA", IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2005). Philadelphia (USA), March 18-23, 2005.

[24] F. Rubio, X. Mestre, "A comparative study of different self-reference beamforming architectures for multicode DS/CDMA", XI National Symposium of Radio Science Poznan Center of Science. Poznan (Poland) April 7-8, 2005.

[25] X. Mestre, M.A. Lagunas, "Finite sample size effect on minimum variance beamformers: optimum diagonal loading factor for large arrays", IEEE Transactions on Signal Processing, pending publication.

[26] A. Gameiro and A. Silva, "Joint STBC and Pre-Filtering Technique for MISO TDD Downlink MC-CDMA Systems", IST Summit on Mobile and Wireless Communications 2005, Dresden, June 2005.

[27] A. Silva and A. Gameiro, "SFBC with Pre-Filtering Technique for DL TDD MC-CDMA Systems in High Data Rate Context", IEEE Globecom 2005, Saint Louis, USA, Nov 2005.

[28] A. Alexiou. C. Papadias, "Reconfigurable MIMO Transceivers for Next-Generation Wireless Systems", Bell Labs Technical Journal, Future Wireless Communications issue, vol. 10, No. 2, pp. 139-156, July 2005.

[29] A.Alexiou, M. Qaddi, "Robust Linear Precoding to Compensate for Antenna Correlation in Orthogonal Space-Time Block Coded Systems", 3rd IEEE Sensor Array and Multichannel Signal Processing Workshop, July 2004.

[30] A. Medles, A. Alexiou. "Linear Precoding for STBC to Account for Antenna Correlation in Next Generation Broadband Systems", IEEE PIMRC 2005, Berlin, September 2005.

[31] A. Alexiou, M. Haardt, "Smart Antenna Technologies for Future Wireless Systems: Trends and Challenges", *IEEE Communication Magazine*, vol.42, No. 9, pp. 90-97, September 2004

[32] A. Alexiou, M. Haardt, "White paper on Smart Antenna, MIMO systems and Related Technologies", *15th WWRF Meeting*, Paris, December 2005.

[33] P. Karamalis, N. Skentos, A. Kanatas, "Selecting Array Configurations for MIMO Systems: An Evolutionary Computation Approach", IEEE Trans. On Wireless Comms, Vol. 3, No 6, Nov. 2004.

[34] P. Karamalis, N. Skentos, A. Kanatas, "Antenna Subarray Formation for MIMO Systems", Joint COST 273/284 Workshop on Antennas and Related Systems Aspects in Wireless Communications, Gothenburg, Sweden, June 7-10, 2004.

[35] P. Karamalis, N. Skentos, A. Kanatas, "Adaptive Antenna Subarray Formation for MIMO Systems", submitted to IEEE Trans. On Wireless Comms.

[36] A.G. Kanatas, K.D. Kyritsis, P.D. Karamalis, N.D. Skentos, P. Zetterberg, "Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance", Invited presentation at the Joint ACE-NEWCOM Workshop, Dresden, 23 June, 2005.

[37] A.G. Kanatas, K.D. Kyritsis, P.D. Karamalis, N.D. Skentos, P. Zetterberg, "Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance", 14th IST Mobile & Wireless Communications Summit, Dresden, Germany, 19-23 June, 2005.

[38] P. Zetterberg, N. Jaldén and M. Bengtsson, "Analysis of Multi-Cell {MIMO} Measurements in an Urban Macrocell Environment", General Assembly of Internation Union of Radio Science (URSI), oct, 2005.

[39] P. Zetterberg, N. Jaldén, "Comparison of Angle-Spread in Outdoor-to-Outdoor and Outdoor-to-Indoor Cases in an Urban Macro-Cell", Wireless Personal Multimedia Communications WPMC, 2005, sep, Aalborg.

[40] P. Zetterberg , N. Jaldén, K. Yu and M. Bengtsson, "Analysis of {MIMO} Multi-Cell Correlations and Other Propagation Issues Based on Urban Measurements", IST Mobile and Wireless Communications Summit, 2005, mar.

[41] A. Kanatas, K. Kyritsis, P. Karamalis, N. Skentos and P. Zetterberg, "Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance", IST Mobile and Wireless Communications Summit, ACE-NEWCOM Session, 2005.

[42] N.D. Skentos, A.G. Kanatas, and P. Constantinou, "MIMO Channel Characterization Results from Short Range Rooftop to Rooftop Wideband Measurements", IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, WiMob 2005, Montreal, Canada, 22-24 August 2005.

[43] Specifications of MUMS [On line] http://www.s3.kth.se/php/index.php?action=publications&cmd=download&id=528&path=/publications/2003/&filename=IR-S3-SB-0316.pdf&format=pdf

[44] A. Alexiou, M. Qaddi, "Re-configurable Linear Precoders to Compensate for Antenna Correlation in Orthogonal and Quasi-Orthogonal Space-Time Block Coded Systems", VTC 2004.

[45] A. Morgado, A. Gameiro A, J. Fernandes, "Constrained Space-Time Zero-Forcing Pre-equaliser for the Downlink Channel of UMTS-TDD", Proc. of the 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications – PIMRC'02, Vol. 3, pp. 1122-1126, Lisbon, Portugal, September 2002.

[46] A. Silva and A. Gameiro, "Prefiltring antenna array for the downlink of TDD MC-CDMA systems", IEEE Proc. of VTC'03 Spring, pp. 641-645, April2003.
[47] P. Zetterberg and B. Ottersten. "The Spectrum Efficiency of a Basestation Antenna Array System for Spatially Selective Transmission". IEEE Transactions on Vehicular Technology, vol. 44, no. 3, Aug, 1995, pp. 651-660.
[48] P. Zetterberg "Mobile Communications with Base Station Antenna Arrays: Spectrum Efficiency, Algorithms and Propagation Models". PhD Thesis, Royal Institute of Technology, TRITA-S3-SB-9712, downloadable from www.s3.kth.se/cgi-bin/signal/getreports.cgi.
[49] P. Zetterberg. "A Comparison of Two Systems for Downlink Communication with Base Station Antenna Arrays". IEEE Transactions on Vehicular Technology, vol. 48, no. 5, Sept., 1999, pp. 1356-1370.
[50] P. Zetterberg, "Wireless Development Laboratory (WIDELAB) Equipment Base", Technical Report, Department of Signals, Sensors and Systems, Royal Institute of Technology, IR-S3-SB-0316. Available from www.s3.kth.se/cgi-bin/signal/getreports.cgi.
[51] P. Zetterberg, "MUMS Documentation", Technical Report, Department of Signals, Sensors and Systems, Royal Institute of Technology, IR-S3-SB-0403, Available on from www.s3.kth.se/cgi-bin/signal/getreports.cgi.
[52] Radiation Group, Polytechnic University of Madrid [Online]. Available: www.gr.ssr.upm.es.
[53] R. Martínez Rodríguez-Osorio, L. García García, A. Martinez Ollero, F.J. García-Madrid Velázquez, L. de Haro Ariet, M. Calvo Ramón, "ADAM: A Realistic Implementation for a W-CDMA Smart Antenna", Eurasip Journal on Applied Signal Processing, Special Issue on Advances in Smart Antennas, 3rd Quarter, 2004.
[54] A. Martínez, L. García, R. Martínez, L. de Haro, M. Calvo, "Effects of Implementation Impairments in the Performance of a W-CDMA Smart Antenna", 2004 IEEE Vehicular Technology Conference.
[55] P. Zetterberg, N. Jaldén and M. Bengtsson, "Analysis of Multi-Cell {MIMO} Measurements in an Urban Macrocell Environment", General Assembly of Internation Union of Radio Science (URSI), oct, 2005.
[56] P. Zetterberg, N. Jaldén, "Comparison of Angle-Spread in Outdoor-to-Outdoor and Outdoor-to-Indoor Cases in an Urban Macro-Cell", Wireless Personal Multimedia Communications WPMC, 2005, sep, Aalborg.
[57] P. Zetterberg , N. Jaldén, K. Yu and M. Bengtsson, "Analysis of {MIMO} Multi-Cell Correlations and Other Propagation Issues Based on Urban Measurements", IST Mobile and Wireless Communications Summit, 2005, mar.
[58] A. Kanatas, K. Kyritsis, P. Karamalis, N. Skentos and P. Zetterberg, "Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance", IST Mobile and Wireless Communications Summit, ACE-NEWCOM Session, 2005.
[59] P. Zetterberg, J. Jaldén, H. Lundin, D. Samuelsson and X. Zhang, "Implementation of SM and RxTxIR on a DSP-Based Wireless MIMO Test-Bed", The European DSP Education and Research Symposium (EDERS), November, 2004.
[60] M. Bengtsson, "From Single Link MIMO to Multi-user MIMO", Proceedings IEEE International Conference on Acoustics, Speech, and Signal Processing, May 2004.
[61] P. Zetterberg, "A Smart Antenna Concept for 4G and Transceiver Cost", Proceedings of Nordic Radio Symposium, Oulo, Finland, August, 2004.
[62] D. Samuelsson, J. Jaldén, P. Zetterberg and B. Ottersten, "Realization of a Spatially Multiplexed {MIMO} System", EURASIP, Journal on Applied Signal Processing, March 2005.
[63] X. Zhang, P. Svedman, H. Lundin and P. Zetterberg, "Implementation of a Smart Antenna Multiuser Algorithm on a DSP-Based Wireless MIMO Test-Bed", Proceedings IEEE International Symposium on Personal Indoor and Mobile Radio Communications PIMRC, September 2005.
[64] ACE Deliverable 2.2-D8, "*Antenna Technology for Reconfigurable Multiple Antenna Terminals".*
[65] S. Yang and J.-C. Belfiore, ``Optimal space-time codes for the MIMO Amplify-and-Forward cooperative channel," IEEE Transactions on Information Theory, Sep. 2005, submitted for publication. Also available on Arxiv (5 Sept. 2005).
[66] C. Abou Rjeily, N. Daniele and J.-C. Belfiore, "Space-Time Coding For Multiuser Ultra-Wideband Communications," IEEE Transactions on Communications, Sep. 2005, submitted for publication
[67] F. Kharrat, S. Fontenelle and J.J. Boutros, ``Accurate approximation of QAM error probability on quasi-static MIMO channels and its application to adaptive modulation," IEEE Transactions on Information Theory, Jun. 2005, submitted for publication.
[68] F. Oggier, G. Rekaya, J.-C. Belfiore, and E. Viterbo, "Perfect Space Time Block Codes," IEEE Transactions on Information Theory, Sep. 2004, submitted for publication

[69] J.-C. Belfiore and A. M. Cipriano, "Space-Time coding for non coherent channels", Chapter 10 of the book "Space-Time Wireless Systems: From Array Processing to MIMO Communications". Editors: H. Boelcskei, D. Gesbert, C. Papadias and A. J. van der Veen. Publisher: Cambridge University Press. Fall 2005.
[70] E. Jandot dit Danjou and J.-C. Belfiore, ``A 2 x 2 antennas Bluetooth system," IEEE Communications Letters, vol. 9, Issue 9, pp. 784-786, Sep. 2005.
[71] J.-C. Belfiore, G. Rekaya, and E. Viterbo, "The Golden Code: A 2 x 2 Full-Rate Space-Time Code with Non-Vanishing Determinants" IEEE Trans. Inform. Theory, vol. 51, Issue 4, April 2005.
[72] I. Kammoun and J.-C. Belfiore, "A new family of Grassmann space-time codes for non-coherent MIMO systems," IEEE Communications Letters, Vol. 7, Issue 11, Nov. 2003, Pages:528 - 530.
[73] M. O. Damen, N. C. Beaulieu, and J.-C. Belfiore, "Bandwidth-efficient linear Modulations for multiple-antenna transmission," IEEE Trans. Inform. Theory, vol. 49, Issue 9, Sept. 2003.
[74] M. O. Damen, Ahmed Tewfik, and J.-C. Belfiore, "A construction of a space-time code based on number theory," IEEE Trans. Inform. Theory, vol. 48, Mar. 2002.
[75] M. O. Damen, K. Abed-Meraim, and J.-C. Belfiore, ``Diagonal algebraic space-time block codes," IEEE Trans. Inform. Theory, vol. 48, Mar. 2002.
[76] M. O. Damen, A. Chkeif, and J.-C. Belfiore," Lattice code decoder for space-time codes," IEEE Communications Letters , Volume: 4 Issue: 5 , May 2000, Page(s): 161-163.
[77] M. O. Damen, K. Abed-Meraim, and J. C. Belfiore, "Generalized sphere decoder for asymmetrical space-time communication architecture", Electronics Letters , Volume: 36 Issue: 2 , 20 Jan. 2000 Page(s): 166 -167.
[78] J. J. Boutros, F. Kharrat and H. Randrianbololona, ``A classification of multiple antenna channels," in 43rd Allerton Conference, Sep. 2005.
[79] S. Yang and J.-C. Belfiore, ``Optimal space-time codes for the amplify-and-forward cooperative channel," in 43rd Allerton Conference, Sep. 2005.
[80] S. Yang and J.-C. Belfiore, ``The impact of channel estimation error on the DPC region of the two-user Gaussian broadcast channel," in 43rd Allerton Conference, Sep. 2005.
[81] D. Champion, G. Rekaya, J.-C. Belfiore and E. Viterbo, ```Partitionning the Golden Code: A framework to construct coded space-time modulation," in Canadian Workshop on Information Theory, Montreal, Jun. 2005.
[82] A. M. Cipriano, I. Kammoun, and J.-C. Belfiore, ``Simplified decoding for some non-coherent codes over the Grassmannian," in ICC 2005 Proceedings, vol. 2, May 2005, pp. 757-761.
[83] H. Laamari, J.-C. Belfiore, and N. Ibrahim, ``Near maximum likelihood detection using an interior point method and semidefinite programming," in Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers, vol. 1, November 2004, pp. 223-226.
[84] G. Rekaya, J.-C. Belfiore, and E. Viterbo, ``Algebraic 3x3, 4x4 and 6x6 Space-Time Codes with Non-Vanishing Determinants," in Proceedings of Intern. Symp. on Inform. Theory and its Applications, ISITA, October 2004, pp. 325-329.
[85] S. Chabbouh, Ph. Ciblat and J.-C. Belfiore, ``Iterative Algorithms for SDP Relaxation Associated with MIMO ML Detection Problem," in Proceedings of Intern. Symp. on Inform. Theory and its Applications, ISITA, October 2004, pp. 601-605.
[86] G. Rekaya, J.-C. Belfiore, and E. Viterbo, ``A Very Efficient Lattice Reduction Tool on Fast Fading Channels," in Proceedings of Intern. Symp. on Inform. Theory and its Applications, ISITA, October 2004, pp. 714-717.
[87] J.-C. Belfiore, G. Rekaya, and E. Viterbo, ``The Golden Code: A 2 x 2 full rate Space-Time Code with non vanishing Determinants," in Proceedings 2004 IEEE International Symposium on Information Theory.IEEE I. T. Society, June 27- July 2 2004.
[88] L. Berriche, K. Abed-Meraim, and J.-C. Belfiore, ``Cramer-Rao bounds for MIMO channel estimation," in Proceedings of ICASSP, May 2004, pp. 397-400.
[89] H. Laamari, J.-C. Belfiore, and N. Ibrahim, ``A generalized branch and bound decoder for asymmetrical space-time communication architecture," in Proceedings of International Conference on Information and Communication Technologies: From Theory to Applications, April 2004, pp. 285-286.
[90] G. Rekaya and J.-C. Belfiore, ``On the complexity of ML lattice decoders for decoding linear full-rate space-time codes," in Proceedings 2003 IEEE International Symposium on Information Theory.ISIT Yokohama, July 2003.
[91] J.-C. Belfiore and G. Rekaya, ``Quaternionic lattices for space-time coding," in Proceedings of the Information Theory Workshop.IEEE, Paris 31 March - 4 April 2003 ITW 2003.
[92] S. Galliou and J.-C. Belfiore, ``A new family of full rate, fully diverse space-time codes based on Galois theory," in Proceedings IEEE International Symposium on Information Theory.IEEE, June 30-July 5 2002, p. 419.

[93] S. Galliou, I. Kammoun, and J.-C. Belfiore, ``Space-time codes for the GLRT noncoherent detector," in Proceedings 2002 IEEE Int. Symp. on Inf. Theory.IEEE, July 2002, p. 77.

References

[94] G. J. Foschini, "Layered space-time architecture for wireless communication in fading environments when using multi-element antennas," Bell Labs Tech. J., pp. 41–59, 1996.

[95] J.Winters, "On the capacity of radio communication systems with diversity in a Rayleigh fading environment," IEEE J. Select. Areas Commun.,vol. 5, pp. 871–878, June 1987.

[96] A. Goldsmith, S. Ali Jafar, N. Jindal and S. Vishwanath, "Capacity limits of MIMO channels", IEEE J. Selected Areas on Commun, pp.684-702, June 2003.

[97] G. J. Foschini, G. D. Golden, R. A. Valenzuela, and P. W. Wolniansky, "Simplified processing for high spectral efficiency wireless communication employing multi-element arrays," IEEE J. Seceted Areas Comm., vol. 17, pp. 1841–1852, 1999.

[98] M. Sellathurai and S. Haykin, "Further results on diagonal-layered space-time architecture," in Proc. VTC 2001 Spring, 2001.

[99] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," IEEE Trans. Information Theory, vol. 44, pp. 744–765, 1998.

[100] J.-C. Guey et al., "Signal designs for transmitter diversity wireless communication system over rayleigh fading channels," in Proc. VTC'96, pp. 136–40..

[101] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block code from orthogonal designs," IEEE Trans. Info. Theory, vol. 45, pp. 1456–67, July 1999.

[102] B. D. Van Been and K. M. Bucley, "Beamforming: A versatile approach to spatial filtering", IEEE ASSP Magazine, vol. 5, pp. 4-24, April 1988.

[103] L. C. Godara, "Application of Antenna Arrays to Mobile Communications, Part I: Performance Improvement, Feasibility, and System Considerations", Proceedings of the IEEE, Vol. 85, Issue 7, pp. 1031-1060, July 1997.

[104] L. C. Godara, "Application of antenna arrays to mobile communications, Part II: Beamforming and Direction of Arrival Consideration", Proc. of The IEEE, vol. 85 pp. 1195-1245, Aug. 1997

[105] R. Esmailzadeh, M. Nakagawa, "PreRAKE Diversity Combining in Time-Division Duplex CDMA Mobile Communications", IEEE Transactions on Vehicular Technology, vol. 48, no. 3, pp. 795-801, May 1999

[106] P. W. Baier, M. Meurer, T. Weber, and H. Tr¨oger, "Joint Transmission (JT), an alternative rationale for the downlink of Time Division CDMA using multi-element transmit antennas," Proc. IEEE ISSSTA, NY, USA, pp. 1–5, 2000.

[107] A. N. Barreto and G. Fettweis, "Capacity increase in the downlink of spread spectrum systems through joint signal precoding," Proc. IEEE ICC, vol. 4, pp. 1142–1146, 2001.

[108] Chen-Nee Chuah, David Tse, Joseph Kahn, Reinaldo Valenzuela, "Capacity Scaling in MIMO Wireless Systems Under Correlated Fading", IEEE Transactions on Information Theory, Vol. 48, No. 3, pp. 637-650, March 2002.

[109] J. Akhtar, and D. Gesbert, "Partial Feedback Based Orthogonal Block Coding," Proc. IEEE 57th Vehicular Technology Conference, VTC'03, April 2003.

[110] Seong Taek Chung; Lozano, A.; Huang, H.C, "Approaching eigenmode BLAST channel capacity using V-BLAST with rate and power feedback", VTC 2001 Fall, Volume: 2 , 7-11 Oct. 2001.

[111] S. A. Jafar, S. Vishwanath and A. J. Goldsmith, "Channel capacity and beamforming for multiple transmit and receive antennas with covariance feedback", ICC 2001, Helsinki, Finland.

[112] K. K. Mukkavilli, A. Sabharwal, and B. Aazhang, "Design of Multiple Antenna Coding Schemes with Channel Feedback," Proc. 35th Asilomar Conference on Signals, Systems and Computers'01, vol. 2, pp. 1009-1013, November 2001.

[113] E. Visotsky, and U. Madhow, "Space-Time Transmit Precoding With Imperfect Feedback," IEEE Trans. On Information Theory, vol. 47, no. 6, pp. 2632-2639, September 2001.

[114] M Skoglund and G Jöngren. On the capacity of a multiple-antenna communication link with channel side information. IEEE Journal on Selected Areas in Communications, 21(3):395--405, April 2003.

[115] G Jöngren, M Skoglund, and B Ottersten. Combining beamforming and orthogonal space-time block coding. IEEE Transactions on Information Theory, 48(3):611--627, March 2002.

[116] G Jöngren and M Skoglund. "Quantized feedback information in orthogonal space-time block coding. Submitted to IEEE Transactions on Information Theory".

[117] I. E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. on Telecommun. (ETT)*, vol. 10, pp. 585–595, Nov.-Dec. 1999.

[118] H. Huang, H. Viswanathan, and G. J. Foschini, "Multiple antennas in cellular CDMA systems: Transmission, detection, and spectral efficiency," *IEEE Trans. on Wireless Commun.*, vol. 1, no. 3, pp. 383–392, July 2002.

[119] R. L. Choi, K. B. Letaief, and R. D. Murch, "MIMO CDMA antenna systems," in *IEEE International Conf. on Commun.*, 2000, vol. 2, pp. 990–994.

[120] M. Ahmed, J. Pautler, and K. Rohani, "CDMA receiver performance for multiple-input multiple-output antenna systems," in *Proc. IEEE Vehicular Technology Conf. - Fall*, 2001, pp. 1309–1313.

[121] C. Li and S. Roy, "Performance of frequency-time MMSE equalizer for MC-CDMA over multipath fading channel," *Wireless Personal Communications*, vol. 18, no. 2, pp. 179–192, Aug 2001.

[122] J. Altuna, B. Mulgrew, and J.M. Zabalegui, "Semi-blind equalisation for multiple-input multiple-output MC-CDMA," in Proc. 3G Mobile Commun. Technol. conf., 2001, pp. 387–391.

[123] IST FITNESS Project, "Link Level performance Analysis of reconfigurable MTMR tranceivers for UMTS", Deliverable D3.1.1, http://www.telecom.ece.ntua.gr/fitness.

[124] G Klang. "On Interference Rejection in Wireless Multichannel Systems", PhD Thesis, Royal Institute of Technology, TRITA-S3-SB-0328, downloadable from www.s3.kth.se/cgi-bin/signal/getreports.cgi.

[125] S. Hara, R. Prasad, "Multicarrier Techniques for 4G Mobile Communications", Artech House, 2003

[126] P.Rooyen, M Lotter, D Wyk, "Space-Time processing for CDMA mobile communications", 2nd Edition, Kluwer, 2001.

[127] N. Yee, J.P.M.G. Linnartz and G. Fettweis, "Multi-Carrier CDMA in indoor wireless Radio Networks", IEEE Personal Indoor and Mobile Radio Communications (PIMRC) Int. Conference, Sept. 1993, Yokohama, Japan, pp. 109-113

[128] A. Paulraj, R Nabar, D. Gore, "Introduction to Space-Time Wireless Communications", Cambridge Press, 2003.

[129] M.Engels "Wireless OFDM Systems: How to Make Them Work?", Kluwer, 2002

[130] R.D.J. van Nee, R. Prasad, R. Van Nee, "OFDM for Wireless Multimedia Communications", Artech House, 2000

[131] L. Hanzo, C.H. Wong, M.S. Yee "Adaptive Wireless Tranceivers", John Wiley & Sons Ltd, 2002

[132] S. Kaiser, " MC-CDMA mobile radio systems – Analysis and Optimization of Detectio, Dcoding, and Channel Estimation", PhD Thesis, 1998

[133] B. Muquet, M. de Courville, P. Duhamel, V. Buzenac. "A Subspace based blind and semi-blind channel identification method for OFDM systems" Proc. SPA WC'99, pages 170-173, May 1999.

[134] U.Tureli "Multicarrier Wireless Systems: Enabling Studies on Crrier Frequency and Channel Estimation", PhD Thesis, 2000.

[135] J. Proakis, "Digital Communications", 3rd edition, McGraw-Hill, 1995

[136] S. Haykin, "Adaptive filter theory", 3rd edition, Prentice Hall, 1996

[137] D Samardzija, N Mandayam, "Pilot Assisted Estimation of MIMO fading channel Response and Achievable Data Rates", IEEE 2003

[138] P.Hoher, S.Kaiser, P Robertson, "Pilot-symbol-aided channel estimation in time and frequency", GLOBECOM'97

[139] S. Kay, "Fundamentals of Statistical Signal Processing: Estimation Theory". Prentice-Hall, New Jersey, USA, 1993.

[140] G. Stuber, "Principles of Mobile Communications", Kluwer, 1996

[141] R. Prasad, L. Muñoz, "WLANs and WPANs towards 4G Wireless" Artech House, 2003

[142] P. Bohlin, M. Tapio. "Performance Evaluation of MIMO Communication Systems based on Superimposed Pilots". Proc. IEEE ICASSP 04, Canada, May 2004.

[143] G. Giannakis, Y. Hua, P. Stoica, L Tong, "Signal processing advances in wireless and mobile communications", Volume 1, Prentice Hall, 2001

[144] A. Moustakas S. Simon A. Sengupta "MIMO Capacity Through Correlated Channels in the Presence of Correlated Interfers and Noise" *IEEE Transactions on Information Theory*, pp. 2545-2561, Oct. 2003

[145] M. Stege, M. Bronzel, and G. Fettweis, "On the performance of space-time blockcodes," in *IEEE Proc. Vehicular Technology Conference*, Rhodes, Greece, 6.-9. May 2001, vol. 3, pp. 2282–2286.

[146] Matthias Stege, Tom Ruprich, Marcus Bronzel, and Gerhard P. Fettweis, "Channel estimation using long-term spatial channel characteristics," in *Proceedings of WPMC*, 2001.

[147] Monica Nicoli and Umberto Spagnolini, "Reduced rank channel estimation and rank order selection for CDMA systems," in *Proceedings ICC*, 2001.

[148] Debajyoti Pal, “Fractionally spaced equalization of multipath channels: a semi-blind approach,” *1993International Conference on Acoustics, Speech and Signal Processing*, vol. 3, pp. 9–12, 1993.

[149] S. Yatawatta and A. Petropulu, “Blind channel estimation in MIMO OFDM systems,” *IEEE*, Nov. 2003.

[150] N. Yee and J.P.M.G. Linnartz, "BER for Multi-Carrier CDMA in indoor Rician-fading channel", Asilomar Conference, Monterey, CA, November 1-3, 1993, pp. 426-430.

[151] N. Yee and J.P.M.G. Linnartz, "Controlled equalization for MC-CDMA in Rician fading channels", 44th IEEE Vehicular Technology Conference, June 1994, Stockholm, pp. 1665-1669.

[152] N. Yee and J.P.M.G. Linnartz, "Wiener filtering for Multi-Carrier CDMA", IEEE / ICCC conference on Personal Indoor Mobile Radio Communications (PIMRC) and Wireless Computer Networks (WCN), The Hague, September 19-23, 1994, Vol. 4, pp. 1344-1347.

[153] X. Deng, A. Haimovich J. Garcia-Frias, “Decision Directed Iterative Channel Estimation for MIMO Systems”, (0-7803-7802-4/03) IEEE, 2003

[154] A. Gorokhov and J.P.M.G. Linnartz, "Robust OFDM receivers for dispersive time varying channels: equalisation and channel estimation", paper 1453, ICC 2002, April 28- May 2, 2002, New York, Session OFDM-2, 29-4.

[155] R. Gaspa, J.R. Fonollosa, “Comparison of Different Transmit Diversity Space-Time Code Algorithms”, pages 503-508, IST2000.

[156] M. Alouini, and A. Goldsmith, “Capacity of Rayleigh Fading Channels Under Different Adaptive Transmission and Diversity-Combining Techniques”, IEEE Transactions on Vehicular Technology, Vol. 48, NO. 4, July 1999

[157] J. Ylitalo, E. Turola, P. Kinnunen, M. Heikkila, K. Majonen, P. Mogensen, X. Mestre, D. P. Palomar, R. Gaspa, A. Perez, M. Lamarca, J.R. Fonollosa, “Definition of power control, channel estimation and SIR estimation principles”, IST-1999-11729 METRA project.

[158] H. Andoh, M. Sawahashi, and F. Adachi, “Channel Estimation Using Time Multiplexed Pilot Symbols for Coherent Rake Combining for DS-CDMA Mobile Radio”, The 8th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 1997. 'Waves of the Year 2000'. PIMRC '97, Volume: 3, 1-4 Sept. 1997, Pages: 954 – 958.

[159] Texas Instruments, “Space Time Block Coded Transmit Antenna Diversity for WCDMA”, ETSI SMG2 UMTS-L1, 14-18 December 1998, Espoo, Finland.

[160] R. Steele, C.-C. Lee, “Closed-Loop power control in CDMA systems”, Communications, IEE Proceedings, Volume: 143, Issue: 4, Aug. 1996 Pages: 231 – 239.

[161] A. F. Molisch, M. Z. Win, J. H. Winters, “Capacity of MIMO Systems with Antenna Selection”, IEEE ICC 2001, Vol. 2, 11-14 June, Pages: 570-574.

[162] D. A. Gore, R. U. Nabar, A. Paulraj, “Selecting an Optimal Set of Transmit Antennas for a Low Rank Matrix Channel”, IEEE ICASSP 2000, Proceedings, Vol. 5, 5-9 June, Pages: 2785-2788.

[163] A. F. Molisch, “MIMO Systems with Antenna Selection – An Overview”, IEEE RAWCON 2003, Aug. 10-13, Pages: 167-170.

[164] D. Gore, A. Paulraj, “Statistical MIMO Antenna Sub-Set Selection with Space-Time Coding”, IEEE ICC 2002, Vol. 1, 28 April – 2 May, Pages: 641-645.

[165] D. Gore, R. Heath, A. Paulraj, “Statistical Antenna Selection for Spatial Multiplexing Systems”, IEEE ICC 2002, Vol. 1, 28 April – 2 May, Pages: 450-454.

[166] R. S. Blum, J. H. Winters, “On Optimum MIMO With Antenna Selection”, IEEE Communications Letters, Vol. 6, No. 8, Aug. 2002, Pages: 322-324.

[167] N. Kong, L. B. Milstein, “Combined Average SNR of A Generalized Diversity Selection Combining Scheme”, IEEE ICC 1998 Record., Vol. 3, 7-11 June 1998, Pages: 1556-1560.

[168] A. Gorokhov, D. A. Gore, A. J. Paulraj, “Receive Antenna Selection for MIMO Spatial Multiplexing: Theory and Algorithms”, IEEE Transactions on Signal Processing, Vol. 51, No. 11, November 2003, Pages: 2796-2807.

[169] A. F. Molisch, M. Z. Win, J. H. Winters, “Reduced-Complexity Transmit/Receive-Diversity Systems”, IEEE Transactions on Signal Processing, Vol. 51, No. 11, November 2003, Pages: 2729-2738.

[170] M. Z. Win, J. H. Winters, “Analysis of Hybrid Selection/Maximal-Ratio Combining in Rayleigh Fading”, IEEE Transactions on Communications, Vol. 47, No. 12, December 1999, Pages: 1773-1776.

[171] M. Z. Win, J. H. Winters, “Analysis of Hybrid Selection/Maximal Ratio Combining of Diversity Branches with Unequal SNR in Rayleigh Fading”, IEEE 49th Vehicular Technology Conference 1999, Vol. 1, 16-20 May, Pages: 215-220.

[172] D. Gore, A. Paulraj, “MIMO Antenna Subset Selection with Space-Time Coding”, IEEE Transactions on Signal Processing, Vol. 50, No. 10, Oct. 2002, Pages: 2580-2588.

[173] N. Kong, T. Eng, L. B. Milstein, "A Selection Combining Scheme For Rake Receivers", IEEE ICUPC 1995, 6-10 Nov., Pages: 426-430.

[174] R. W. Heath, S. Sandhu, A. Paulraj, "Antenna Selection for Spatial Multiplexing Systems with Linear Receivers", IEEE Communications Letters, Vol. 5, No. 4, April 2001, Pages: 142-144.

[175] A. Paulraj, D. Gore, "Optimal Antenna Selection in MIMO Systems with Space-Time Block Coding", IEICE Trans. Commun., Vol. E84-B, No. 7, July 2001, Pages: 1713-1719.

[176] R. W. Heath, A. Paulraj, "Antenna Selection for Spatial Multiplexing Systems Based on Minimum Error Rate", IEEE ICC 2001, Vol. 7, 11-14 June, Pages: 2276-2280.

[177] A. Gorokhov, "Antenna Selection Algorithms for MEA Transmission Systems", IEEE ICASSP 2002, Vol. 3, 13-17 May, Pages: III-2857 – III-2860.

[178] A. Ghrayeb, T. M. Duman, "Performance Analysis of MIMO Systems with Antenna Selection over Quasi-Static Fading Channels", IEEE Transactions on Vehicular Technology, Vol. 52, No. 2, March 2003, Pages: 281-288.

[179] M. Han, "Antenna Selection in MIMO Systems", Unpublished

[180] A. Gorokhov, D, Gore, A. Paulaj, "Performance Bounds for Antenna Selection in MIMO Systems", IEEE ICC 2003, Vol. 5, 11-15 May, Pages: 3021-3025.

[181] M. F. Sabir, "Antenna Selection for Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing Systems", Submitted for publishing.

[182] A. Papathanassiou, M. Meurer, T. Weber, and P. Baier, "A Novel Multiuser Transmission Scheme Requiring No Channel Estimation and No Equalisation at the Mobile Stations for the Downlink of TD-CDMA Operating in TDD mode", Proc. IEEE 52nd Vehicular Technology Conf. – VTC Fall'00, vol 1, 203-210, October 2000.

[183] B.R. Vojcic, W.M. Jang, 'Transmitter Precoding in Synchronous Multiuser Communications,' IEEE Transact. on Communications, vol. 46, no. 10, pp. 1346-11355, Oct. 1998.

[184] T. Salzer, D. Mottier and D. Castelain, "Comparsion of antenna array techniques for the downlink of multicarrier CDMA systems", IEEE Proc. of VTC'03 Spring, pp. 316-320, April2003.

[185] E. Visotsky, and U. Madhow, "Space-Time Transmit Precoding With Imperfect Feedback," IEEE Trans. On Information Theory, vol. 47, no. 6, pp. 2632-2639, September 2001.

[186] R. Irmer, W. Rave and G. Fettweis, "Minimum BER transmission for TDD-CDMA in frequency-selective" channels", Proc. of PIMRC'03, pp. 12060-1264, Sept. 2003.

[187] J. K Cavers, "Single user and multiuser adapative maximal ratio transmission for Rayleigh channels", IEEE Trans on Veh. Tech, vol. 49, pp.2043-2050, Nov 2000.

[188] M. Schubert and H. Bovhe, "Solution of the multiuser downlink beamforming problem with individual SINR constraints" IEEE Trans on Veh. Tech, vol. 43, pp.18-28-Jan. 2004.

[189] S. Verdu "Multiuser detection", Cambridge University Press, 1998.

[190] E. Visotsky, and U. Madhow, "Space-Time Transmit Precoding With Imperfect Feedback," IEEE Trans. On Information Theory, vol. 47, no. 6, pp. 2632-2639, September 2001.

[191] E. Moulines, P. Duhamel, J.F. Cardoso, S. Mayrargue, "Subspace methods for the blind identification of multichannel FIR filters," IEEE Trans. Signal Proc., Vol.43, pp. 516-525, Feb. 1995.

[192] G.Xu, H.Liu, L.Tong, T. Kailath, "A least-squares approach to blind channel identification," IEEE Trans. Signal Proc., Vol.43, pp. 2982-2993, Dec. 1995.

[193] J.L. Valenzuela, A. Valdovinos, F.J.Casedevall "Performance of blind equalization with higher order statistics in indoor radio environments," IEEE Trans. Vehicular Technology, Vol.46, pp. 369-374, May 1997.

[194] [J. Ayadi, D.T.M. Slock, "Blind multichannel estimation and joint order detection by MMSE ZF equalization," IEEE Vehicular Technology Conference, Vol.1, Sept.19-22, 1999.

[195] C. Gao; M. Zhao; "Blind channel estimation algorithm for MIMO-OFDM systems", Electronics Letters, VOL. 39, NO. 19, Sept. 2003.

[196] Y. Zeng, T. Sang Ng, "Blind channel estimation method tolerating order overestimation", The 8th International Conference on Communication Systems, 2002.

[197] W.H. Gerstacker, D.P. Taylor, "Blind channel order estimation based on second-order statistics," IEEE Trans. on Signal Processing Let., Vol.10, pp. 39-42, Feb. 2003.

[198] D. N. Kalofonos, M. Stojanovic, and J. G. Proakis, "On the performance of adaptive MMSE detectors for a MC-CDMA system in fast Rayleigh channels", Proc. of PIMRC'98, pp.1309-1313, Sept. 1998.

[199] V. Kuhn, "Iterative interference cancellation and channel estimation for coded OFDM-CDMA", Proc. of ICC '03., pp. 2465-2469, May 2003.

[200] H. Bing, X. Gao, Y. Xiaohu, J. Wang and E. Costa, “An iterative joint channel estimation and symbol detection algorithm applied in OFDM system with high data to pilot power ratio”, Proc. of ICC '03., pp. 2076-2080, May 2003.

[201] S. Y Park, Y. Kim, C. Kang and D. Kang,“ Iterative receiver with joint detection and channel estimation for OFDM system with multiple receiver antennas in mobile radio channels”, Proc. of GLOBECOM '01, pp.3085-3089, Nov. 2001

[202] K. Abed-Meraim, E. Moulines, and P. Loubaton, “Prediction error method for second-order blind identification, IEEE Trans. Signal Processing”, vol. 45, pp. 694-705, Mar. 1997.

[203] K. Abed-Meraim, P. Loubton , and E. Moulines, “A subspace algorithm for certain blind identification problem”, IEEE Trans. Information Theory, vol. 32, no 2, pp. 499-511, Mar. 1997

[204] W. Jeon, K. Paik and Y. Cho, “An Efficient Channel Estimation Technique for OFDM Systems with Transmitter Diversity”, Personal, Indoor and Mobile Radio Communications PIMRC, Sept. 2000.

[205] M. Kiessling and Joachim Speidel, “Statistical Transmit Processing for Enhanced MIMO Channel Estimation in Presence of Correlation”, IEEE GLOBECOM conference, 2003.

[206] M. Shin, H. Lee and C. Lee, “Enhanced Channel-Estimation Technique for MIMO-OFDM Systems”, IEEE Transaction on Vehicular Technology, vol. 53, No. 1, Jan. 2004.

[207] Ye Li, J. Winters, N. Sollenberger, “MIMO-OFDM for wireless communications: signal detection with enhanced channel estimation”, IEEE Transaction on Communications, VOL. 50, NO.9, Sep, 2002.

[208] Ye Li, and H. Wang, “Channel estimation for MIMO-OFDM Wireless Communications”, Personal, Indoor and Mobile Radio Communications”, PIMRC 2003.

[209] Y. Zen and T. Ng, “Blind MIMO Channel Estimation Method Tolerating Order Overestimation”, The International Conference on Communication Systems, ICCS 2002, pp. 274-278.

[210] Ye Li, “Simplified Channel Estimation for OFDM Systems with Multiple Transmit Antennas”, IEEE Transaction on Wireless Comunications, Vol. 1, No. 1, Jan. 2002.

[211] G Raleigh and S.N. Diggavi and V.K Jones and A Paulraj, "A Blind Adaptive Transmit Antenna Algorithm for Wireless Communication", Proceedings IEEE International Conference on Communications, 1995.

[212] D Gerlach and A Paulraj. "Adaptive Transmitting Antenna Arrays with Feedback",vol 1, no 10, IEEE Signal Processing Letters". Oct, 1994, pp. 150-152.

[213] K. Siamitros, “Rapid Prototyping in MIMO”, The Institute of Communications and Radio-Frequency Engineering, Technical University of Wien, May 2004.

[214] M. Beach, C. Simmonds, P. Howard, P. Darwood, “European Smart Antenna Test-Bed-Field Trial Results”, IEICE Trans. Commun., vol. E84-B, no. 9, pp. 2348-2356, September 2001.

[215] H. Sampath, S. Talwar, J. Telleado, V. Erceg, A. Paulraj, “A fourth–generation MIMO-OFDM broadband wireless system: Design, Performance, and field test results trials”, IEEE Communications Magazine, vol. 40, no. 9, pp. 143-149, Sept. 2002.

[216] E. Aschbacher, S. Caban, C. Mehlfürer, G. Maier, M. Rupp, “Design of a flexible and scalable 4×4 MMO test-bed”, Proc. of the 11th IEEE Signal Processing Workshop (DSP 2004), New Mexico, USA, Aug. 2004.

[217] R. Arnott, S. Ponenkanti, “Experimental investigation of adaptive antennas in a real DCS-1800 mobile network”, Proc. 3rd ACTS Mobile Communications Summit, pp. 535-543, Rhodes, Greece, June 1998.

[218] Maxime Guillaud, Suman Das, Andreas Burg, Markus Rupp, Eric Beck, “Rapid Prototyping Design of a 4 × 4 BLAST-over-UMTS System”, Proc. 35th Asilomar Conference on Signals, Systems and Computers, pp. 1256-1260, Pacific Grove, CA, November 4-7, 2001.

[219] Smart Antenna Research Laboratory, Georgia Institute of Technology [Online]. Available: http://users.ece.gatech.edu/~mai/sarl.htm.

[220] T. Horseman, J. Webber, M.K. Abdul-aziz, R. Piechocki, M. Beach, A. Nix, P. Fletcher, “A Software And Hardware Evaluation of Revolutionary Turbo MIMO OFDM schemes for 5GHz WLANs”, 57th IEEE Vehicular Technology Conference, (VTC 2003-Spring), vol. 4, pp. 2788–2792, Jeju, Korea, April 2003.

[221] J.W. Wallace, B.D. Jeffs, M.A. Jensen, “A real-time multiple antenna element test-bed for MIMO algorithm development and assessment”, Proc. 2004 IEEE Antennas and Propagation Society International Symposium, Monterey, CA, June 2004.

[222] SmART-Antenna, University of Duisburg [Online]. Available: http://smart.uni-duisburg.de/index_e.html.

[223] Communication Technology Laboratory, Communication Theory Group, Swiss Federal Institute of Technology Zurich [Online]. Available. http://www.nari.ee.ethz.ch/commth/.

[224] MASI-Multiple Antenna System for ISM-Band Transmission, Prof. Dr.-Ing. K.D. Kammeyer, Department of Communications Engineering, University of Bremen [Online]. Available: http://www.ant.uni-bremen.de/masi/.

[225] Fall, Los Angeles, CA, 26-29 September, 2004.

[226] A. Adjoudani, E.C. Beck, A.P. Burg, G.M. Djuknic, T.G. Gvoth, D. Haessig, S. Manji, M.A. Mildbrot, M. Rupp, D. Samardzija, A.B. Siegel, T. Sizer II, C. Tran, S. Walker, A. Wilkus, P.W. Wolniansky, "Prototype Experience of MIMO Blast over Third-Generation Wireless System", IEEE Journal on Selected Areas in Communications, vol. 21, no. 3, pp. , April 2003.

[227] Institute of High Frequency Technology, RWTH Aachen University [Online]. Available: http://www.ihf.rwth-aachen.de.

[228] J.B. Andersen, J.Ø. Nielsen, G.F. Pedersen, K. Olesen, P. Eggers, E.H. Sørensen, S. Denno, "A 16 by 32 Wideband Multichannel Sounder at 5 GHz for MIMO", Proc. 2004 IEEE Antennas and Propagation Society International Symposium, Monterey, CA, June 2004.

[229] K. Sakaguchi, J. Takada, K. Araki, "A Novel Architecture for MIMO Spatio-Temporal Channel Sounder", IEICE Trans. Electron., vol. E02–C, no. 3, pp. 1-6, March 2002.

[230] R.S. Thomä, D. Hampicke, A. Richter, G. Sommerkorn, "MIMO Vector Channel Sounder Measurement for Smart Antenna System Evaluation", European Transactions on Telecommunications, Special Issue on Smart Antennas, ETT, Vol. 12, No.5, pp. 427- 438, Sept./Oct. 2001.

Acronyms/Terminology

AMC	Adaptive Code Modulation
ADC	Analog-to-Digital Converter
BER	Bit Error Rate
BLAST	Bell Labs Layered Space Time
BS	Base Station
CAD	Computer Added Design
CDMA	Code Division Multiple Access
CSC	Conventional Selection Combining
CSI	Channel State Information
DCA	Digital-to-Analog Converter
DS-CDMA	Direct Sequence CDMA
DOA	Direction Of Arrival
DSP	Digital Signal Processing
E field	Electric field
EM	Electromagnetic field
FDD	Frequency Division Duplex
FPGA	Field-Programmable Gate Array
GSC	Generalized Selection Combining
HS-MIMO	Hybrid-Selection MIMO
HS-MRC	Hybrid-Selection Maximal Ratio Combining
MAI	Multiple Access Interference
MC-CDMA	Multicarrier CDMA
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MRC	Maximal Ratio Combining
MS	Mobile Station
MUD	Multiuser Detection
OFDM	Orthogonal Frequency Division Multiplexing
OTD	Orthogonal Transmit Diversity
PIC	Parallel Interference Cancellation
QPSK	Quadrature Phase Shift Keying
SAR	Specific Absorption Rate
SDMA	Spatial Division Multiple Access

SDR	Software Defined Radio
SER	Symbol Error Rate
SIC	Serial Interference Cancellation
SIMO	Single Input Multiple Output
SIP	Super-Imposed Pilot
SIR	Signal to Interference Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
ST	Space Time
STC	Space Time Code
STTD	Space Time Transmit Diversity
SUD	Single User Detection
TDD	Time Division Duplex
TSTD	Time Switched Time Diversity
UTMS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
WLAN	Wireless Local Area Network
WMSA	Weighted Multi-Slot Averaging
ZF	Zero Forcing