The MIMOWA Project: a Step Towards the Real Implementation of MIMO Techniques in Future Wireless Systems

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Abstract: Multiple-input multiple-output (MIMO) is a radio antenna technology which employs multiple antennas at both transmitter and receiver ends, and provides new enhancements and potentials in communication systems. Under the framework of the MEDEA+ program, the MIMOWA project has two main objectives. First, it aims at the definition, design, and demonstration of MIMO techniques for the 3G LTE and WiMAX standards. The second objective is to investigate and propose advanced designs and techniques for future wireless standards. This paper provides an overview of the work that has been done in the context of the MIMOWA project, towards the achievement of these two objectives.

Keywords: MIMO, WiMAX, LTE

1. Introduction

Future wireless communication systems are expected to offer highly reliable broadband radio access in order to meet the increasing demands of emerging high speed data and multimedia services. In the last few years multiple-input multiple-output (MIMO) systems, which deploy spatially separated multiple antenna elements at both ends of the transmission link, have emerged as one of the most promising approaches for high data rate and more reliable wireless systems.

The MIMOWA (“MIMO technologies for Wireless Access”) project aims at contributing to the development and research work in this area at the European level. This project is being developed under the framework of the MEDEA+ program (Eureka, project 2A103) and the consortium is composed of 10 companies (manufacturers, operators, equipment providers, etc.), 3 Universities, and 1 research center from 6 different countries.

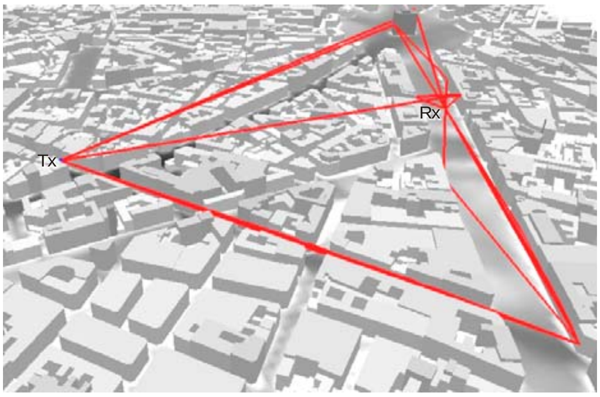

Figure 1: Multi-path propagation in urban environment.

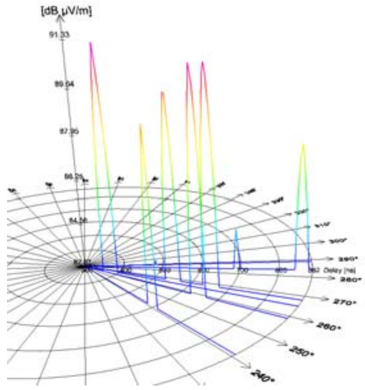

Figure 2: Spatial channel impulse response.

The main focus of the project is twofold. On the one side, work has been done on the definition, the design, and the development/demonstration of MIMO techniques for the 3G LTE ("Long Term Evolution") [1,2] and WiMAX ("Worldwide Interoperability for Microwave Access") [3] standards. The final objective is to prove, by means of a set of real demonstrators and testbeds, that the use of the MIMO technology in these standards is affordable from both technical and commercial points of view. On the other hand, the MIMOWA project also aims at providing and proposing advanced designs and techniques for future wireless standards, i.e. a more research oriented work has also been performed.

Before entering the core of the paper, let us mention that, in order to assess the benefits of the MIMO technology, realistic models of the wireless propagation channel are required. In general, the radio propagation is subject to multi-path, i.e. the signal from the transmitter propagates along different paths to the (mobile) receiver. In many cases there is no direct line-of-sight (LOS) and the only paths connecting transmitter and receiver are reflected, diffracted, and scattered at a number of different obstacles (see Fig. 1). Deterministic propagation models are generally based on ray-optical techniques where different rays emitted by the transmitting antenna are subject to reflection, scattering, and diffraction at walls and edges of buildings and similar obstacles. In the context of the MIMOWA project, the most crucial parameters of the spatial channel, including angular spread (see Fig. 2) and the MIMO capacity have been simulated based on ray tracing models. Corresponding MIMO channel data is used in the channel emulator of the demonstrators.

In the remainder of this paper, we present first the work that has been done in relation with the WiMAX and LTE standards, and then, the main lines of research conducted within the project are described briefly.

2. WiMAX

2.1 - General aspects

The current standard for metropolitan area networks, IEEE 802.16e [4], base of the well-known WiMAX Mobile System Profile [3], provides orthogonal frequency division multiple access (OFDMA) allowing efficient resource sharing and coping with multipath propagation in dense urban environments. WiMAX also allows for multiple antenna solutions which can be exploited to improve radio links.

[4] provides a plethora of possible multi antenna schemes to either increase throughput or robustness, including space time/frequency transmit diversity, space time block coding (STBC), frequency hopping diversity coding, and spatial multiplexing (SM). The most known example of STBC corresponds to Alamouti's scheme for the case of 2 transmit antennas [5], whereas for the case of SM, the interested reader can refer to [6,7].

The main advantage of STBC, and Alamouti's code as an example, is its robustness in the sense that the equivalent channel seen after the decoding is flattened, i.e., the probability of having a deep fade is significantly reduced. Note, however, that this scheme is not able to increase the throughput in spite of having more antennas. On the other side, SM can increase the throughput by a factor equal to the number of antennas, but does not have any robustness capability. It is also important to mention that there exist techniques and combinations providing a trade-off between throughput and robustness.

Worldwide interoperability and reduced complexity are the targets of the WiMAX forum. Therefore just a small subset of the proposed MIMO schemes was decided to be part of WiMAX. In the downlink, the chosen modes are STBC for robustness and single user SM for increased throughput. In the uplink, collaborative SM is the only selected mode.

2.2 – WiMAX demonstrator

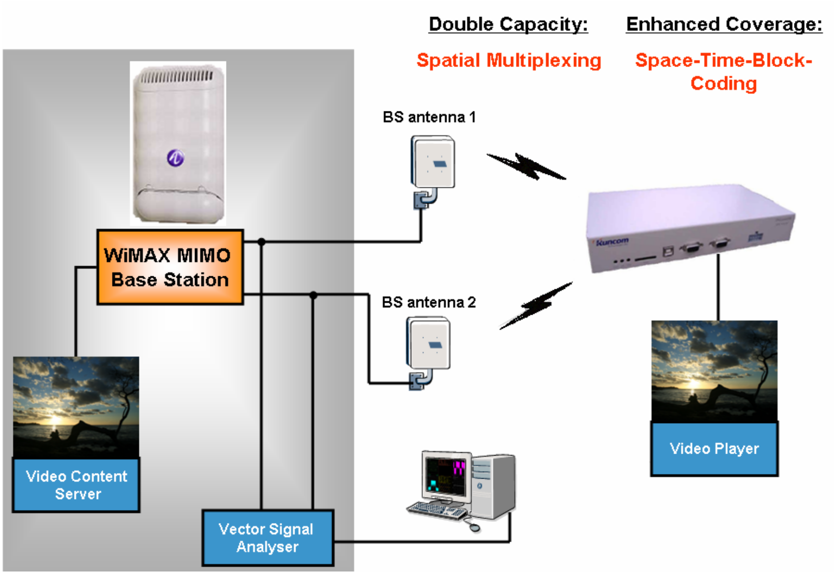

Figure 3: Demonstration setup for a WiMAX system in the MIMOWA project.

As commented in the introduction, one of the major objectives of the MIMOWA project is to develop several demonstrators in order to prove the feasibility of implementing MIMO with real standards. Concerning WiMAX, one of the targets is the demonstration of adaptive switching of the MIMO operation mode of a radio link between STBC and SM according to the current propagation conditions. The terminal reports to the base station which mode it prefers. Based on this feedback, the appropriate mode is selected. Fig. 3 shows the setup of the demonstrator. In STBC mode, one video stream is transmitted, whereas in SM mode two videos can be sent simultaneously. As long as the channel conditions allow for, SM MIMO is maintained. If the prerequisites are not fulfilled anymore, the link falls back to STBC. In this case, one video stream is not affected at all, but the transmission of the other stream is interrupted.

Going into more details, concerning the implementation of the receiver, a scheme supporting both partial usage of subcarriers (PUSC) and adaptive modulation and coding (AMC) subchannelization modes has been developed.

The computational complexity is mainly found in processing blocks of a receiver such as channel estimation, MIMO techniques (e.g. space-time block decoding) and memory controllers implemented in various stages of a system. The design methodology that was followed (i.e. co-simulation of the Matlab model versus the behavioral VHDL model) was proved to be very efficient. Advanced implementation techniques were used throughout the design stage to minimize utilization of FPGA resources. The real-time operation of the system together with the stringent specifications of the mobile WiMAX receiver implied a design approach of zero latency memory access as far as the embedded memories are concerned. This in turn has dramatically increased the implementation complexity of the control plane of the memory system. Generally speaking, the design and implementation complexity was proved to be very high and truly challenging.

Regarding the RF design of the system, also included in the development, it is important to remark that WiMAX brings new advantages with respect to WiFi but also hard obstacles which must be overcome. Multiple band plans and channel bandwidths, adaptive data modulations, multi-user access, scalability, mobility, and longer range imply RF challenges for the transceiver architecture and subsystems. Moreover a MIMO transceiver design must deal with high integration, low-power consumption, and prevention of coupling effects.

The higher number of OFDM subcarriers, smaller subcarrier spacing, and mobility Doppler effects demand high performance frequency synthesizers with better phase noise and a better carrier/sampling frequency offset (CFO/SFO) performance in order to avoid symbol constellation rotation and intercarrier interference. WiMAX demands higher dynamic range, sensitivity (and thus better noise figure), larger power back-off at transmission, higher power amplifier linearity and bandwidth without penalizing power consumption, and broad automatic gain control (AGC) range. Amplifier saturation and noise figure degradation (noise foldovers and reciprocal mixing effects) need to be carefully considered by the filtering strategy. Besides, there is significant probability of interference between WiFi and WiMAX networks operating at very close frequency separation.

3. LTE

The 3GPP-LTE represents the next step forward in the mobile communications industry. The first specification is being finalized within 3GPP Rel-8. The overall target is to select and specify a technology that meets the increased carrier and end-user needs and at the same time enables a smooth transition to 4G. The LTE radio access network will substantially improve end-user experience and spectral efficiency:

- reduced latencies (<50–100 ms connection delay, <10 ms transmission delay from terminal to server),
- support for scalable bandwidths of 1.4, 3, 5, 10, 15, 20 MHz,
- peak data rate scaling with bandwidth and number of MIMO layers: absolute peak rates are 300 Mb/s (4 layers, downlink) and 75 Mb/s (1 layer, uplink) in the 20 MHz channel,
- higher (cell edge) user throughput and higher spectrum efficiency: 3 to 4 times more efficient than HSDPA Rel. 6 and 2 to 3 times more efficient than HSUPA Rel. 6.

The LTE physical layer employs some advanced technologies from cellular radio, such as OFDMA and MIMO in the downlink (DL) and single carrier FDMA (SCFDMA) in the uplink (UL). In the UL only antenna selection is specified, i.e., a single spatial layer [1]. Different MIMO techniques are envisaged [2]: transmit (Tx) diversity (TD), SM and beamforming (BF). Both, open loop (OL) and closed loop (CL) SM are possible.

The OFDM-based radio access offers advantages, such as robustness against multi-path interference, flexible resource allocation, and high quality of reception through soft-combining of broadcast/multicast signals. Challenges for user terminal (UT) implementation include an efficient realization of channel estimation and MIMO detection and a turbo decoder which needs to handle data rates of up to 75 Mbps per spatial stream.

Finally, we remark that the OFDM-based radio access makes LTE totally different from previous cellular standards which mainly use time/frequency-division multiple-access (GSM/EDGE) or code-division multiple-access (UMTS/HSPA). Thus, except for a few techniques like turbo coding, existing 3GPP Rel-7 implementations cannot be reused.

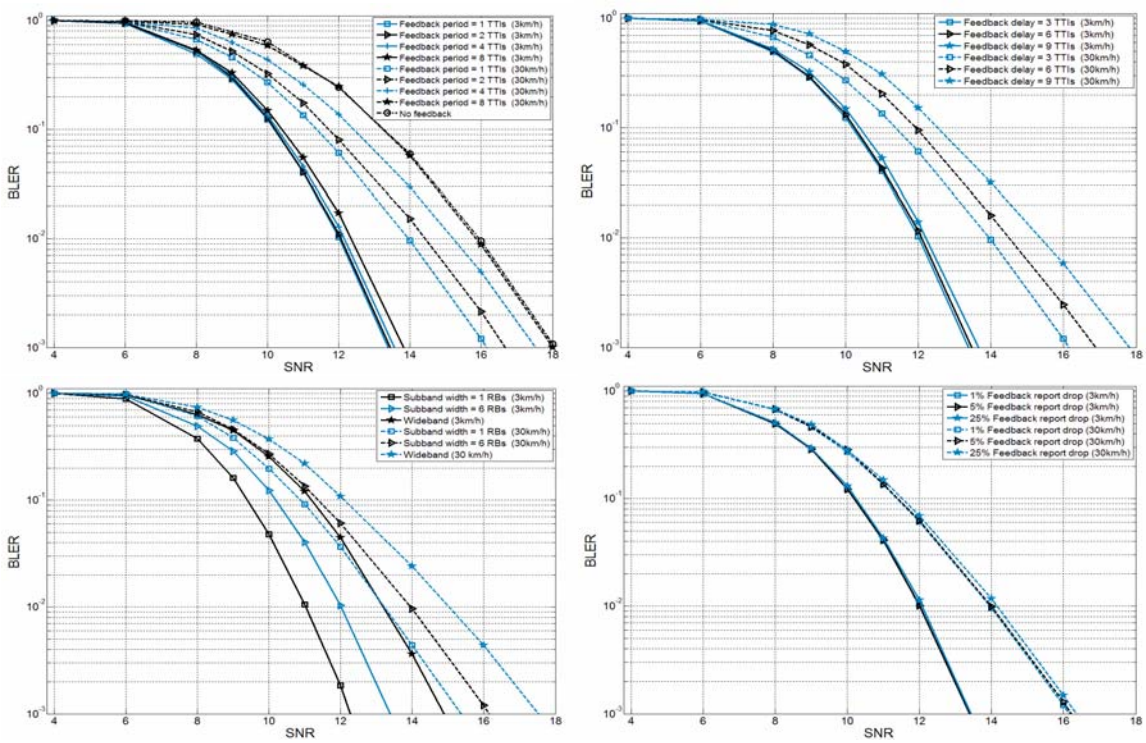

Figure 4: Block error rate over SNR for different feedback delay and period parameters.

3.1 – Closed loop MIMO limitations

Considering the different possible MIMO techniques, the best suitable for the current scenario should be chosen. This is only possible if these techniques have been investigated at different scenarios. Here, CL-MIMO will be further investigated. Main features of LTE single-user CL-MIMO are precoding, multiple-codeword transmission (allowing for 'per codeword' link adaptation and automatic repeat request operations), and rank adaptation with the possibility to adaptively change the number of spatially multiplexed streams.

Practical limitations and overhead trade-offs have to be taken into account when studying real-life CL-MIMO performance. In order to minimize the amount of feedback overhead, several compression mechanisms are selected for LTE, such as codebook-based precoding, variable feedback period, and frequency clustering, taking into account the coherence bandwidth and coherence time of the channel. Furthermore, the loop delay generally limits performance in fast changing environments.

In the context of the MIMOWA project, the performance impact of some of the parameters has been evaluated. As it can be seen in Fig. 4, the feedback delay and period parameters show an increasing sensitivity with the speed of the mobile. At 30km/h, CL-MIMO gains over OL-MIMO for the fastest update rates only. In rich scattering channel conditions, the results show a large degradation of performance when increasing the frequency granularity. Up to 2.5 dB are observed at 10^{-3} BLER (block error rate) between a frequency selective and a wideband report. Finally, it is observed that the reporting errors have a limited overall impact, even at 30km/h.

3.2 - MIMOWA closed loop LTE demonstrator

Also within the framework of the MIMOWA project, a joint demonstrator has been built, emphasizing the benefits of CL-MIMO in LTE for streaming video applications. To show its dynamic aspect, the demonstrator includes a 2x2 channel emulator as well as a feedback interface for fast adaptations of the signal. The channel conditions are obtained through ray tracing based simulations. The transmitted signal is generated using hardware acceleration. The receiver can operate in real time.

4. Future MIMO Technologies

The second objective of the MIMOWA project is the investigation of future air interface possibilities based on the MIMO techniques in order to provide higher data rates, extend coverage, and improve link reliability. In this section, first, some of the most promising MIMO techniques for next implementations in multi-user environments are described. Second, some advanced issues related to future MIMO systems are discussed.

4.1 - Promising MIMO techniques for multi-user environments

Multi User MIMO (MU-MIMO) is one of the most promising transmission schemes offering a significant increase in spectral efficiency. It is an advanced MIMO transmission method in which both the base station (BS) and the UTs are provided with multiple antennas. This allows the BS to transmit simultaneously in time and frequency several streams to each user in a SM approach. The transmitter is able to control and minimize the multi-user interference (MUI) by designing properly the beamformer applied to each of the streams for each user. This means that the beams conveying the information to the i^{th} UT nulls out at the direction of all other active UTs (null steering). In this scenario, **Space Division Multiple Access** (SDMA) is a special case where each UT is equipped only with one antenna and, therefore, only one stream of information is sent to each user. Thanks to this, no SM detector is required and SISO terminals can be re-used.

Receive Beamforming with interference nulling has become one of the prominent methods for interference mitigation in communication systems. It has been long known that adequate complex weighting of an antenna array results in an equivalent directional antenna. Similarly, complex weighting of an antenna array may lead to the formation of spatial nulls, suppressing the radiation from a certain direction. When the desired sources and interferers are spatially separated, it is possible to apply beamforming techniques to enhance the communications link.

A **Distributed MIMO** system, as opposed to a concentrated MIMO system, consists of one BS with more than one antenna that establishes links with a number of UTs with just one antenna. Distributed MIMO systems aim to improve the overall efficiency (bit/s/Hz over the cell) by enabling more than one simultaneous communication. The capacity of these systems is nearly the addition of the capacity of the individual links in absence of the other transmitters [8]. The distributed MIMO system that has been modeled in the context of the MIMOWA project consists of a TDD OFDM system with four antennas at the BS and four UTs being serviced at the same time and frequency. Just as an example, in the uplink of an IEEE 802.11 system, all the UTs transmit their own standard packets at the same time, the BS estimates the MIMO channel and uses that information to recover the received data packets and to preequalize the downlink transmission so that each UT can decode its own data packets with a standard WiFi receiver. The benefits derived from the use of this distributed MIMO system is that it is based only on additional complexity at the BS while the modifications needed at the UT are negligible. Therefore, a deployment of such a distributed MIMO system would not mean an increase of the cost of the UTs, and could be immediately employed by investing in infrastructure. The simulation results have shown that this technique is feasible, although some specific issues arise such as the presence of different local oscillators (frequency offsets) or the synchronization of the UTs.

SDMA and distributed MIMO techniques are oriented to keep the user terminal simple, improving the spectral efficiency of the downlink. One remarkable difference is that SDMA systems are based on nulling the interference of the links within the different terminals while distributed MIMO downlink is based on taking advance of the real-time channel estimations to generate constructive interferences while communicating with the terminals.

4.2 - Advanced issues for future MIMO systems

The MIMO techniques presented in the previous subsection assume that a perfect channel state information at the transmitter (CSIT) is available, which is unrealistic. In the context of the MIMOWA project, first, we have developed techniques for providing a quantized version of the channel response to the transmitter, and, second, we have reconsidered the design of MIMO techniques which would be **robust** to the **quantized CSIT**:

- In FDD systems, a possible way to make channel knowledge available at the transmitter is through a feedback channel from the receiver. Although in the literature there are solutions for feedback design which are optimum for some kind of design criteria and channel statistics [9], a general solution is still missing. We have developed a feedback and quantization strategy for single-user systems which is general and can be applied to any design criteria. The strategy exploits the inherent structure of the instantaneous channel correlation matrix (which is the CSIT needed) in order to apply an efficient differential quantization based on geodesic curves that is able to follow channel variations [10]. Numerical simulations have shown the benefits of this technique.
- Since any feedback procedure implies a quantization of the channel response, an error or noise in the CSIT will always appear. In this sense, several robust designs have been proposed being characterized by the fact that they are less sensitive to imperfections in the channel knowledge. One example is a multi-user adaptive beamforming design, where the robustness consists in counteracting the beamforming pointing errors due to mismatches between the CSIT and the actual channel [11]. Additionally, robustness has been also been applied to other schemes such as multi-beam opportunistic to develop a strategy which is able to allocate dynamically feedback bits among users taking into account energy-related aspects for the whole radio network [12].

Another problem which has been investigated, is the use of a **cross-layer criterion** for optimizing a MIMO single-user transmission. The criterion proposed is called *goodput*, defined as the number of information bits delivered without error to the user by unit of time. For this system-based criterion to make sense, it has to take into account the presence of error-correction and frame retransmission mechanisms; i.e., the goodput criterion has to be cross-layer oriented. In a MIMO system with error-correction and automatic repeat request (ARQ) retransmission protocol, the goodput maximization problem can be tackled by jointly maximizing the bit rate for a target BER, and by tuning the value of the target BER. The maximization of the bit rate in a MIMO system yields to a diagonalization of the MIMO channel by using the left/right singular vectors of the MIMO matrix for pre/decoding [13]. The outcome is a set of parallel frequency-flat subchannels. Then, the problem of maximizing the goodput in a coded parallel subchannels with ARQ has been discussed in [14]. It was shown that the waterfilling with adequate value of the target BER is near-optimal, and that the near-optimal value of the target BER depends on the error-correction code used, the frame length, the type of ARQ protocol used, the available transmit power, and the channel state.

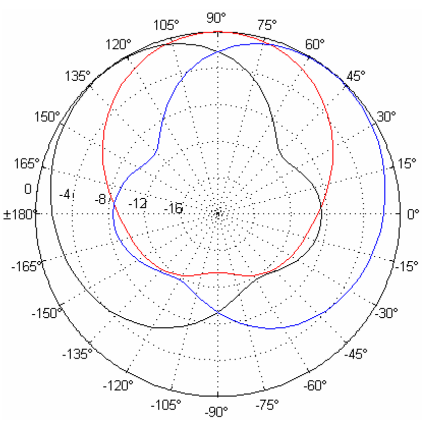

Figure 5: Beamforming on a terminal model at 2 GHz. H-Cut, 90° front, 180°/0° left/right, -90° back (head of user).

Finally, another issue which has been investigated is the **antenna design**, which can have a great influence on the MIMO channel capacity. When they are placed closely together, which is the usual case for a mobile terminal, effects like coupling and correlation arise. This has to be taken into account to achieve full MIMO efficiency. These effects have been studied and techniques have been developed to compensate for. Furthermore, methods have been developed which allow a limited beamforming with the antenna arrangement. This can be used anyway to improve diversity- and MIMO-performance. As an example, Fig. 5 shows three possible beams on a terminal model with a size of a typical PDA. With such a configuration the whole usable azimuth range can be covered.

5. Conclusions

MIMO is meant to be the new technique for the next wireless communication standards. It will be needed to manage many users at the same time and serve them with high data rates without using additional radio resources. In the context of the MIMOWA project, this paper demonstrates the theoretical functionality of MIMO in WiMAX and LTE systems considering all system components. Besides, the demonstrator developed in the project will help to show the practical benefits of MIMO.

Multiple data streams over the same frequency are transmitted which makes MIMO totally different to common radio systems. The receiver must distinguish the received data streams from each other, which is only possible with low correlated channels and special coding. Otherwise the transmit scheme must be changed. In the MIMOWA project new techniques have been investigated to handle the difficulties of MIMO. The paper also shows which MIMO technologies can be used in the future to increase data rates, increase spectral efficiency, extend coverage, and improve link reliability.

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