MIMAX – Exploiting the maximum performance and minimum system costs of wireless MIMO systems

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Abstract: MIMAX aims at developing a pervasive, low-power consuming and low-cost MIMO network platform with reliable data-rate of up to 100 Mb/s in environments with strong multipath and coverage ranges up to several hundred meters. For this purpose, novel signal processing concepts in the analogue RF domain and reconfigurable base band algorithms are used to exploit the maximum performance of MIMO systems but keeping needed additional complexity at a minimum. Supported by market studies, the platform will be benchmarked to state-of-the-art systems with respect to the performance enhancements in mobile wireless networks.

Keywords: wireless communication, MIMO systems, power efficient communication.

1. Introduction

As today's computing is expected to become more and more ubiquitous oriented, decentralised mobile and wireless networks will become more important than today. Market analyses predict promising perspectives for such networks with data speeds up to the Gb/s range [1,2] in the next years. Such high data rates can be achieved by exploiting the large bandwidth available at very high frequencies, e.g. at 60 GHz or above. However, the corresponding hardware is expensive, the power consumption is high, and the coverage range and reliability of these networks is rather limited that might delay the market introduction of such concepts. A promising concept mitigating these drawbacks is the multiple-input multiple-output (MIMO) approach, where multiple independent data streams and/or multiple antenna signals based on one single data stream are transmitted and processed using smart algorithms [3].

If multiple transmitted signals are combined intelligently at the receiver, intersymbol interferences in scenarios with strong multipath are compensated thereby improving the reliability of the wireless link with respect to a specified data speed and bit error rates [4]. Furthermore, independent data streams transmitted over a rich-scattering MIMO channel enhance the maximum possible data rates. In state-of-the-art combining approaches, the signal processing is performed in the baseband that offers the advantage of a simple design using commercially available off-the-shelf components.

Unfortunately, to exploit the benefits of *n* antenna paths, the number of components, power consumption and costs are multiplied by a factor of *n* because almost all paths are operating in parallel and the synergies of the paths are very low. Theses drawbacks have delayed the exploitation of adaptive antenna approaches within the mass-market.

MIMAX mitigates the drawbacks of conventional adaptive combining concepts by performing adaptive weighting of the complex signal vectors in the radio front-ends of the transmitter (TX) and receivers (RX). Analogue signal processing in the RF domain reduces the system components and its complexity to a minimum and, consequently, the power consumption, the system costs and size can be significantly reduced compared to the state-of-the-art achieving similar performance as full baseband MIMO systems.

Several challenges are associated with the MIMAX approach where a major challenge is the design of compact, low-cost, and low power transceiver supporting this concept together with the integration of the antenna array, the base band and MAC processor. This challenge is addressed during the next three years of the project.

2. Objectives

The innovations of MIMAX are performed on several networks layers to improve the performance of mobile wireless networks, but keeping simultaneously the system size, the costs and the power consumption at a minimum. The integrated network platform will be benchmarked with respect to state-of-the-art wireless systems where typical performances measurements such as power consumption, reliability of the network links, data throughput and the quality of the links will serve as evaluation criteria.

In this context, full baseband MIMO and single-input single-output (SISO) systems are used for these investigations. Different network scenarios are explored including indoor LANs with high reliability where multipath effects severely impact wireless networks and outdoor MANs in which the system gain, the coverage range and the data rates can be increased.

From these two complementary scenarios, it can be concluded that the requirements of the network dynamically change over time. Various reconfigurable signal processing strategies are implemented to take advantage of integrated MIMAX transceiver in point-to-point and multi-user links as well as in decentralised or centralised networks. These techniques enable advanced network operability such as high data rates and improved quality of communication links and are discussed in section 3.

Table 1: MIMAX objectives compared to state-of-the-art systems

Parameter	Compared system	Quantitative advancement
Power consumption (or battery life time)	Baseband combining	Reduction by a factor > 2 (Improvement by a factor > 2)
Reliability (probability to reach a certain performance)	Without adaptive combining	Improvement by a factor > 3
Data throughput in environments with strong multipath	Without adaptive combining	Improvement by a factor > 3
Quality of service (SNR)	Without adaptive combining	Improvement by a factor[1] $\min(n_t,n_r) < \text{gain} < n_t * n_r$

Table 1 shows a detailed summary of the objectives in MIMAX. It is expected that MIMAX enables a longer lifetime of the mobile devices compared to state-of-the-art network devices with full baseband MIMO. Furthermore, the throughput and the reliability of the links are expected to be increased by a factor three compared to SISO systems. Moreover, MIMAX improves the quality of the links in wireless mobile networks where the quantity of this improvement depends on the current channel characteristics.

Thus, MIMAX allows comprising the benefits of both systems, full baseband MIMO and SISO, in a single network platform. The pursued concept enables reaching similar or identical performances of full baseband MIMO systems whereas only a slightly increased system size, network costs and power consumption compared to SISO systems is achieved.

Figure 1 shows a classification of MIMAX with respect to both competitive systems. Because the combining of the transmitted and received signals is performed in the analogue RF domain, MIMAX does not need multiple parallel receiving or transmitting branches. Therefore, the complexity of the system is kept at a minimum which results into reduced costs and power consumption. Compared to a SISO system, the small hardware overhead consists of the additional equipped antennas and the combining circuits. Especially, in low and medium SNR regimes MIMAX will achieve the same performances as full baseband MIMO because the algorithms are identical.

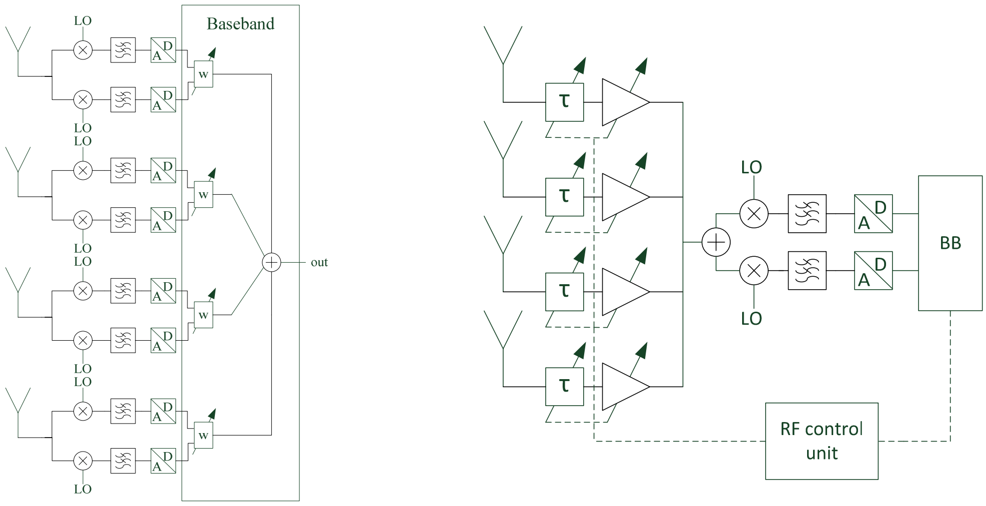
Figure 1: Performances versus cost for SISO, MIMAX using diversity MIMO techniques, and a conventional baseband MIMO scheme.

3. Methodology

The development of the integrated transceiver incorporates several challenges on multiple networks layers, starting from the physical layer up to the transport layer. The overall objective is to achieve reliable transmission with increased data speeds and improved network operability with respect to the reliability of wireless communication links at the end of the project.

To increase the data throughput of the wireless network devices and to improve the reliability of their communications links, adaptive signal processing is applied at the TX and the RX side [3]. Figure 2 shows the MIMAX concept in relation to state-of-the-art systems[2].

In a conventional full baseband MIMO system, the adaptive signal processing is performed in the digital baseband because antenna combining in the baseband has the advantage of a simple design using commercially available off-the-shelf components. This strategy demands for one receiving or transmitting path for each antenna. Therefore, applying the signal processing already in the analogue RF domain comprises several benefits because the multiple parallel receiving or transmitting paths reduce to a single path only. Merely additional circuits for performing the combining in the RF domain are needed.



a) *b)*

Figure 2: Concepts of MIMO system approaches. a) state-of-the-art concept using baseband combing and parallel receiving branches; b) MIMAX approach performing combining in the analogue domain reducing the receiving parts to its minimum.

Compared to smart antenna systems, where the antenna paths are selected and switched, or phased arrays, where only the phase is adjusted, both the phase and amplitudes of the signal vectors are adjusted in MIMAX. Nevertheless, the digital signal processing determines the weighing of each antenna signal for the optimal signal combining due to the current channel characteristics as it is indicated in Figure 2b).

Depending on the particular environment, indoor or outdoor, user movements or scatterers, the channel characteristics change over time. Therefore, the base band and MAC processor has to select the most suitable signal processing algorithms in a seamless fashion depending on several factors such as the number of used antennas, the number of supported users, the environment properties, the network type (ad hoc, cellular), etc. The MAC processor has an IEEE 802.11 conformant interfaces including a base band processor supporting the new RF front-end with new MIMO algorithms.

The use of multiple antennas at the TX and RX can be exploited to obtain array gain, multiplexing gain and diversity gain. Array gain can be obtained due to the presence of multiple antennas at the TX and RX side resulting in power gain. Multiplexing gain permits to increase the data rate by transmitting multiple streams over the channel modes and diversity gain increases the reliability of the communications by improving the quality of the wireless channel.

To obtain these gains, it is necessary to use some type of coding algorithms along space and time in the base band and, in general, there is a trade-off between the multiplexing and diversity gains. Moreover, the space and time encoders must operate separately (the former works in the RF domain and the latter works in baseband), and at different time scales: the spatial encoder or RF beam former must remain fixed during the transmission of a probably large number of symbols, whereas the time-encoder can work at the symbol rate.

Furthermore, among all MIMO algorithms that use a single channel mode for transmission, the so-called dominant eigenmode transmission (DET) provides the best performance. It maximises the output signal-to-noise-ratio (SNR) at the RX at the expense of the highest complexity in point-to-point communications, because it requires perfect channel state information at both the TX and the RX sides.

DET is able to provide full array gain and full spatial diversity by transmitting over the strongest MIMO channel mode. Moreover, in the low and medium SNR regime, the performance of DET is close to the MIMO multi-stream based algorithms [5,6]. In the

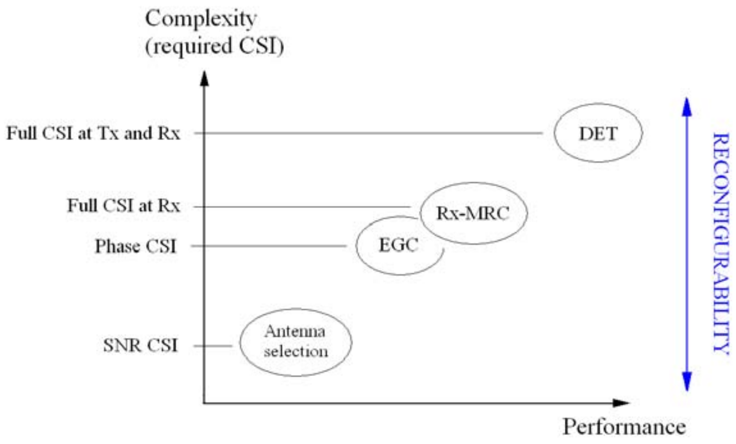


Figure 3: Reconfigurable transmission strategies in MIMAX for optimal performances depending on the channel response.

particular cases of multiple-input single-output and single-input multiple-output configurations DET reduces to the transmit-maximal ratio combining (MRC) and receive-MRC, respectively, that are optimum in terms of capacity [5][6]. Suboptimal diversity schemes based on only-receive-MRC, equal-gain combining or antenna selection are also considered because, in certain cases, they can provide performances closed to DET with lower complexity and lower requirements about the channel state information.

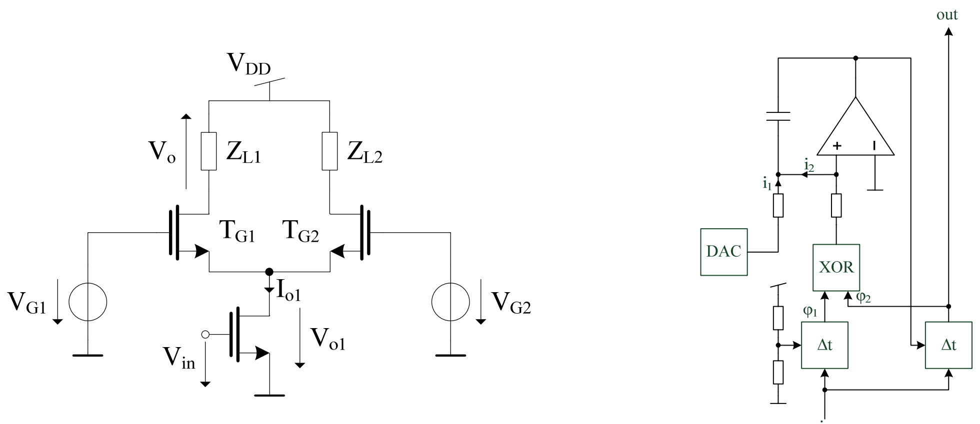
In this context, it can be shown that although the multiplexing gain of the MIMAX transceiver is limited to one, the full spatial diversity of the MIMO channel can still be achieved and, furthermore, the received SNR through array gain can be increased. Specifically, when perfect channel state information is available only at the receiver a novel concept, orthogonal beam division multiplexing (OBDM) significantly improves the system performance. With this scheme the symbols are time-precoded with a unitary discrete Fourier transform matrix, then they are successively transmitted through orthogonal directions and, finally, a receiver comprising maximal ratio combining can be used followed by a minimum mean-square error decoder. The performance of OBDM in terms of outage capacity and bit error rate is significantly better compared to single antenna systems but only minor deteriorated compared to full MIMO systems in which combining is performed in the base band.

Therefore, the MIMAX transceiver is reconfigurable in the sense that it is able to switch among the above MIMO transmission strategies as a function of the channel response and the required quality of service (see Figure 3). Using these algorithms in combination with the analogue signal processing in the RF domain, such arrays achieve similar performance as full MIMO systems with the same low costs of single antenna platforms whereas the complexity of the signal processing can be reconfigured and adjusted to the current channel characteristics.

4. Technology development

The architecture of the key subsystems in the MIMAX RF front-end is shown in Figure 4. MIMAX already performs essential parts of the signal processing in the RF domain and, thus, synergies between the parallel transmit and receive paths of the antenna array can be exploited. Therefore, several subsystems can be shared among the parallel antenna paths, e.g. the analogue-to-digital converter, the mixer, etc., reducing the system complexity, size and power consumption compared to commercially available transceiver systems.

For the MIMAX concept, in the transceiver each antenna signal of the receiver or transmitter has to be multiplied by a complex weight, or in particular each signal has to be amplified and shifted in its phase relatively to the other paths (Figure 4). The major



a) *b)*

Figure 4: Architecture of RF front-end key subsystems. a) amplitude weighting with low phase variation based on constant biasing concept; b) phase linearisation and stabilisation based on a delay-locked loop.

scientific challenge of physical layer comprises the development of the adaptive antenna combining circuits in the radio front-end. Here, precise phase control with 360° control range and amplitude control of more than 20 dB has to be provided by the analogue circuitry. Ideally, e.g. in baseband combining, the phases and the amplitudes can be adjusted independently from each other. Unfortunately, especially in integrated solutions, phase shifters exhibit significant amplitude variations, the amplitude control is imposed by phase variations and finally process variations affect the control range [7,8]. Furthermore, such circuits have been implemented in III/V-technologies that require high cost production and are not suitable for the mass-market.

Within the project duration, adaptive combining circuits are designed in SiGe-BiCMOS-technology, which allows an integrated low cost solution. Due to the lower Q-factor of varactors and variable loads, stronger degradations are expected in silicon compared to III/V-semiconductors. Consequently, to compensate these impairments, innovative concepts have to be applied for the phase (Figure 4b) and amplitude control circuits (Figure 4a).

To relax the specifications for the phase shifters, the phase shift can be performed by adjusting the phase in the local oscillator path and by quadrupling the frequency of the voltage controlled oscillator. Thus, the phase is multiplied by a factor of 4 [7-9] and, whence, only a 90° phase shift is required for full 360° phase control relaxing the challenges. Because the RF signal is mixed with this LO signal, the RF phase is determined by the LO phase and amplitude variations in this concept are compensated because the mixer operates in saturation. Additional requirements of the phase shifter consist of a linear tuning characteristic and a self-calibration with respect to the input frequency but can be achieved by the concept of Figure 4b).

Moreover, the amplitude has to be controlled in the RF path, for noise reasons preferable after the low noise amplifier. Because of bias changes during gain control, the phase of variable gain amplifiers or attenuators is varied [7,9]. In MIMAX, a biasing concept capable of compensating corresponding phase variations was developed (Figure 4) and measurements show an amplitude control over 20 dB with phase variation below ± 2°.

Besides the analogue circuitry, compact and low cost antenna arrays are designed and optimised for WLAN 802.11a standard at 5.5 GHz because of its high commercial market segment. The primary aim is to reduce the correlation among the received signals in this frequency range. This is achieved by exploiting various forms of diversity that arise due to the availability of multiple antennas, like space diversity (spacing antennas far apart), pattern diversity (using antennas with different or orthogonal radiation patterns), and polarisation diversity (using antennas with different polarisations). Previous researches clearly showed the benefits of pattern diversity over space diversity. While the latter is viable only when sufficient real estate is available, pattern diversity can be utilised even in the case where space is limited – like in cellular phones or handsets.

5. Markets and applications

From a consumer market point of view, the MIMAX transceiver can be integrated in any emerging wireless communication standards and networks and several advantages are achieved by the RF combining approach. E.g., the SNR of each communication link can be increased enabling high capacity networks and, in this context, the better SNR enables lower bit error rates and less effort in error correcting codes is needed. Besides the capacity, the coverage range can be increased because wireless standards allow directed transmissions at larger output powers. Therefore, destinations can be reached which would be unreachable in the omnidirectional case and, consequently, the need for relaying and relaying strategies is decreased. As a result, the network infrastructure can be much simpler, less protocol overhead and computing power is needed. Therefore, MIMAX is very attractive for mobile devices but it can be applied to the base stations and the infrastructure as well.

At the moment, the concept is developed for WLAN 802.11a around 5.5 GHz because of its large economic market potential for end-users but the concept can be applied to any other wireless communication standard, such as GSM, UTMS, LTE, etc. Besides the large interest from the end-user in the 802.11a standard, the wavelength of the 5.5 GHz band allows the use of several antennas in a compact system size, e.g. in a PDA or PCMCIA form factor. At lower frequencies, the correlation between the antennas limits the size of the antenna array and because of the tiny form factor in mobile phones, the benefit of multi antenna systems is restricted compared to WLAN. Nevertheless, the MIMAX transceiver can be used in GSM or UMTS base stations and it enables a benefit for the transmitter side. Because multi antenna systems can be fruitfully exploited in base and mobile station simultaneously and because of the high economic interest of the end-users, 802.11a WLAN was chosen for a demonstration of the concept.

Table 2: Applications of MIMAX with large and growing market potential

Application	Network type/Requirements
Wireless applications on third generation platforms (UMTS/WLAN) for mobile communications services, e.g. field force services for SMEs **mobile workers** or **mobile augmented reality**	**Business**, **reliable** operation
Multimedia streaming applications for the business market	**Business**, high **capacity** and **throughput**
Wireless sensors networks for context aware applications	**Business**, **reliable** operation, large **number of users**
Wireless location-aware services with multimedia content, e.g. GeoLoc	**Business** and **private networks, high capacity, coverage range**
Broadband-for-all, e.g. **eLearning**, **eHealth** and **eGovernment**	**Private,** networks in areas where market and business sizes cannot bear such expenditure
Triple Play service with VoIP, broadband internet and **IPTV**	**Private**, high **capacity** and **throughput, reliability**
Smart home services	**Private**, **reliable** operation, large **number**

Application	Network type/Requirements
	of users

Table 2 provides an overview of possible applications for the MIMAX transceiver. An example of Table 2 is wireless Triple Play that includes telephony, high-speed broadband internet and IP television, and will be available to the end-user at home, at work, and while travelling in the bus or car using a mobile phone or PDA. Furthermore, smart home services are enabled where high speed data transmission structures allow multiple phones, data streams, IP television, internet access, video cameras and more, to operate simultaneously, while being routed over a single connection.

A further example in the area of business networks is a platform for field force automation supporting wireless technologies and location based services. This application is based on a monitoring module, which allows tracing of mobile units with the support of a GPS device. Knowing the current position, location-aware multimedia content can be applied to the user and mobile augmented reality can be supported. It is considered demonstrating the benefits of the MIMAX transceiver in these application scenarios at the end of the project.

6. Conclusions

With its innovative concept of signal processing in the analogue front-end, MIMAX reduces the requirements of the digital signal processing hardware in the base stations and in the mobile devices of wireless networks. As a result, the system is reduced in size and power consumption but it achieves comparable performances in reliability, throughput and quality of service compared to state-of-the-art MIMO systems.

Therefore, an integrated WLAN 802.11a transceiver using RF combining for MIMO communication is developed in SiGe-BiCMOS technology. Together with new baseband algorithms and a reconfigurable 802.11a MAC processor, the frond-end is able to react on the recent channel properties and to maximize reliability and throughput.

Consequently, MIMAX enables novel types of applications in private and business networks such as wireless Triple Play or mobile augmented reality where the WLAN 802.11a standard around 5 GHz is addressed. Nonetheless, because of the universal approach, this concept can be applied to other communication standards such as GSM, UMTS, LTE or WiMAX.

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