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Experimental evaluation of an RF-MIMO transceiver for 802.11a WLAN

Ó. González[1], J. Gutiérrez[1], J. Ibáñez[1], L. Vielva[1], R. Eickhoff[2]
[1]*Department of Communications Engineering, University of Cantabria,*
39005 Santander, Spain
Email: {oscargf, jesusgt, jesus, luis}@gtas.dicom.unican.es
[2]*Chair for Circuit Design and Network Theory, Dresden University of Technology,*
01062 Dresden, Germany
Email: ralf.eickhoff@tu-dresden.de

Abstract: In this paper we evaluate the real-time performance of a MIMO-enhanced 802.11a transceiver based on analog combining techniques. The aim of this transceiver design is to achieve higher performance than conventional 802.11a systems while keeping costs and power consumption similar. Also, the demonstrator used to carry out this evaluation is presented, as well as its implementation over a dual band MIMO testbed. Moreover, a series of experiments conducted on nomadic indoor scenarios have led us to results that corroborate the expected analog combining benefits.

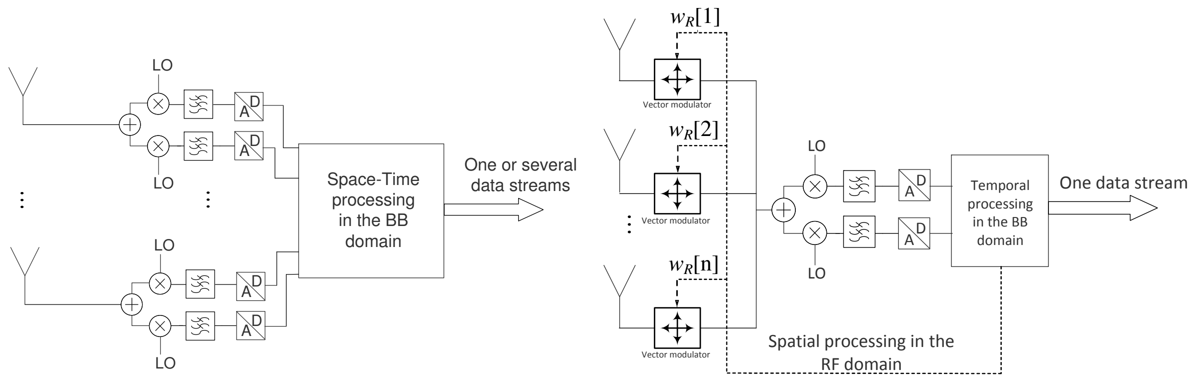
Keywords: IEEE802.11a, MIMO, beamforming, RF combining, channel estimation, FPGA, testbed.

1 Introduction

Wireless communication networks represent a rapidly growing market in which multiple-input multiple-output (MIMO) communication [1][2] approaches are deployed, because they enable higher capacity, better reliability and a large number of supported users. Besides these benefits, MIMO techniques in wireless networks require more complex systems compared to single-input single-output (SISO) approaches. Proof of this is the need of parallel paths at both transmit and receive sides as the number antennas used for communication increase, entailing higher power consumption and costs.

Shifting this paradigm to the analog RF domain involves a reduction of the number of receive and transmit paths to a single one. In this context, the EU funded project Advanced MIMO Systems for MAXimum Reliability and Performance (MIMAX) [3] develops an innovative low power and ultra compact MIMO transceiver where adaptive weighting of the transmitted or received signals is performed in the analog RF domain [4]. This approach allows exploiting spatial diversity and array gain, which results in improved signal-to-noise ratios (SNR) and, therefore, higher throughput, better reliability and a larger coverage range of the communication links.

A complete 4×4 MIMO-enhanced 802.11a demonstrator has been integrated into a dual band (2.4/5 GHz) testbed allowing to test, in real time and under real scenarios, the baseband (BB) algorithms. The real-time part of the demonstrator consist of two main elements: a transmitter emulator (running in the Field-Programable Gate Array (FPGA) of the transmit board) and a receiver emulator (running in the FPGA of the receive board). These emulators make use of a conventional 802.11a baseband processor, implementing its functionalities and signal processing chain defined by the 802.11a/g standard. Furthermore, the MIMO features required by the analog combining architecture are emulated into the FPGA by integrating newly designed blocks.



(a) Traditional full MIMO BB combining strategy. (b) Novel MIMO RF combining strategy.

Figure 1: Architecture of different combining strategies according

The paper is organized as follows. An introduction and background in RF combining concepts is briefly revised in Section 2. Section 3 describes the MIMO-enhanced 802.11a demonstrator, highlighting its structure and presenting the measurement procedure. The measured parameters are shown and analyzed in Section 4. Finally, the obtained conclusions are put forward in Section 5.

2 RF-MIMO concept

The use of multiple antennas at wireless access points and mobile terminals offers an extra spatial dimension which can be exploited to improve reliability (diversity), transmission rate (multiplexing) and coverage (array and coding gains). The analog combining concept studied within the MIMAX project may provide benefits in comparison with single antenna terminals in terms of better coverage, enhanced reliability, increased transmission range and interference reduction (since less transmit power is scattered in unintended directions by using transmit beamforming).

Unlike conventional MIMO systems, in which combining and processing of the antenna signals is performed in the digital baseband as depicted in Figure 1(a), the main novelty of the studied transceiver consists in shifting the spatial processing of the signals to the analog front-end (AFE) as shown in Figure 1(b). Developing such a complex analog front-end is quite challenging as shown in [5]. Nevertheless, this evolution simplifies the transceivers hardware by reducing the number of baseband chains to a single one. Moreover, the processing hardware is simplified because only temporal signal processing is needed. As a result, system size diminishes as well as power consumption and costs.

In contrast to traditional SISO systems, this concept requires a larger number of RF chains and a weighting mechanism that is translated into higher power needs and higher costs. However, the performance is noticeable improved. Of course, this concept is not supported by commercially available solutions but it is also interesting to keep backward compatibility with 802.11a legacy terminals whenever possible.

Before implementing the first MIMO-enhanced 802.11a device, the design of a demonstrator is necessary to corroborate the RF-MIMO concept feasibility. Moreover, a demonstrator allows to assess design decisions by testing the system under realistic conditions.

3 Demonstrator description

In this section the demonstrator shown in Figure 2 is described. The basis of this demonstrator is a commercially available testbed (Subsection 3.1) that does not support the RF combining concept. To overcome the constraints imposed by this hardware, a real-time emulator (Subsection 3.2) of the RF-MIMO paradigm has been integrated into programmable logic. With this approach only one baseband chain is used. So, there is no difference between a final transceiver and the emulated one in terms of link performance but in power consumption and system size.

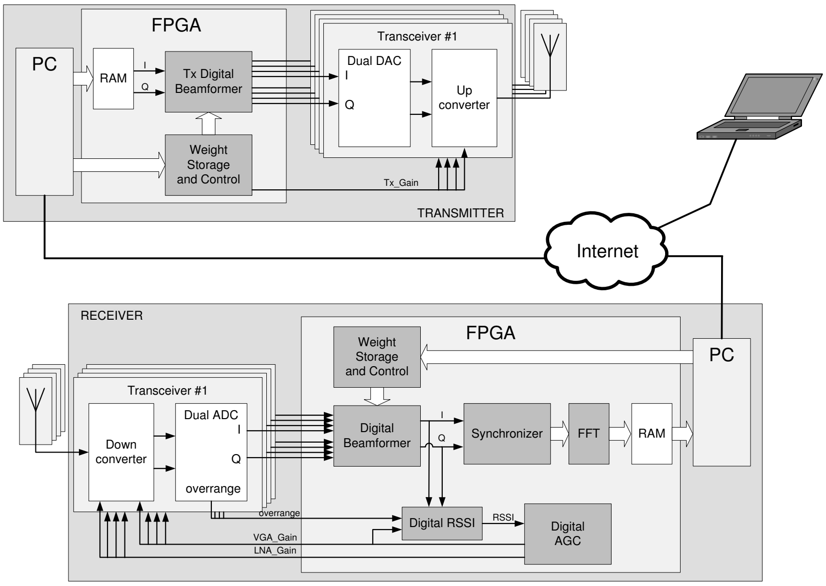


Figure 2: Block diagram of the MIMAX demonstrator

3.1 MIMO testbed

Our hardware setup consists of a MIMO testbed which is made up of two nodes. These nodes can operate at both the 2.4 GHz and the 5 GHz Industrial, Scientific and Medical (ISM) bands, and are able to transmit and receive complex baseband data samples using up to 4×4 antennas. Each node is based on modules by Lyrtech Inc., including a PC, a digital-to-analog converter (DAC) board, an analog-to-digital converter (ADC) board and an analog front-end (AFE).

The platform contains FPGAs for fast processing of the baseband signals. The FPGA at the transmitter side is interfaced with a generation board equipped with eight 14-bit DACs. Similarly, the FPGA at the receiver is interfaced with a board including eight 14-bit ADCs.

The AFE consists of four independent upconversion/downconversion RF chains. It is entirely based on four MAX2829 single-chip RF transceivers covering the ISM frequencies of 2.4 GHz to 2.5 GHz and 4.9 GHz to 5.875 GHz and supporting up to 40 MHz channel bandwidth. It has been used in combination with commercial Skycross antennas and a multiband antenna array specifically designed for this application.

In order to conduct MIMO platform experiments in a flexible way, a remote control software based on web-services has been developed. The functionalities documentation and several examples can be accessed through the following link:

`http://www.gtas.dicom.unican.es/testbed`

Using this remote control architecture it is possible to perform a large variety of experiments including, for example, the demonstrator described in this paper. Moreover, using this web-based remote control software, all partners of the MIMAX consortium have access to the MIMO platform in order to make its own experiments.

3.2 Real-time emulator

The core component of this demonstrator is the 4x4 RF-MIMO real-time emulator design. This design is needed in order to test the baseband algorithms independently of the RF circuitry as well as to validate the real-time implementation of a complete MIMO-enhanced transceiver baseband processor blocks. Thus, using this emulator the final behaviour of a transceiver can be tested without using an AFE with analog combining capabilities.

The baseband processor blocks can be separated into two different subsets: those that provide 802.11a full compliance and those that enhance the transceiver performance supporting the RF combining concept presented in Section 2. The former is a standard 802.11a baseband processor developed by IHP Electronics [6] while the latter are some newly created MIMAX modules by GTAS group at University of Cantabria [7]. In fact, as the final objective is to emulate the RF antenna combining scheme, the emulator uses only essential parts of that baseband processor. Specifically, as shown in Figure 2, 802.11a synchronizer (including frame detection and frequency/time synchronization) [8] and FFT are used, as well as digital beamformers and weight storage and control blocks. Besides, at the receiver side, a specific digital block has been implemented in order to provide a valid RSSI signal for the conventional AGC block of the 802.11a baseband processor. This signal is constructed based on the combined I/Q received signal, the overrange bits of the ADCs and the VGA Gain setting.

Regarding its operation, must be highlighted that TX emulator is needed to generate four different complex baseband signals multiplying the original complex baseband signal (I,Q) by four 16-bit complex weights. These values emulate the complex RF weights to be applied by the analog RF circuitry. The resulting baseband signals are upconverted using the AFE of the MIMO testbed. After downconversion, the RX emulator acquires the four received signals and combines them by multiplying by a given set of complex weights. Moreover, these weights can be applied on a symbol-by-symbol basis (i.e., a different weight can be applied during each received OFDM symbol, as MIMAX does) or even on a sample-by-sample basis (i.e., different weights can be applied at each baseband sample).

At present, the mentioned weight values are calculated offline (running a beamforming algorithm) using Matlab, using either floating-point or fixed-point implementations. This offline execution of the beamforming algorithm provides a large flexibility because it allows to test several beamforming schemes and make comparisons among them. We denote as beamforming scheme a specific selection of weights for each one of the Tx/Rx antennas, in pursuit of certain improvement.

3.3 Procedure description

Once the FPGAs have been programmed using the blocks described in Section 3.2, all emulator hardware is ready to run a procedure (depicted in Figure 3) controlled by a PC that runs a software that emulates higher layer protocols commands.

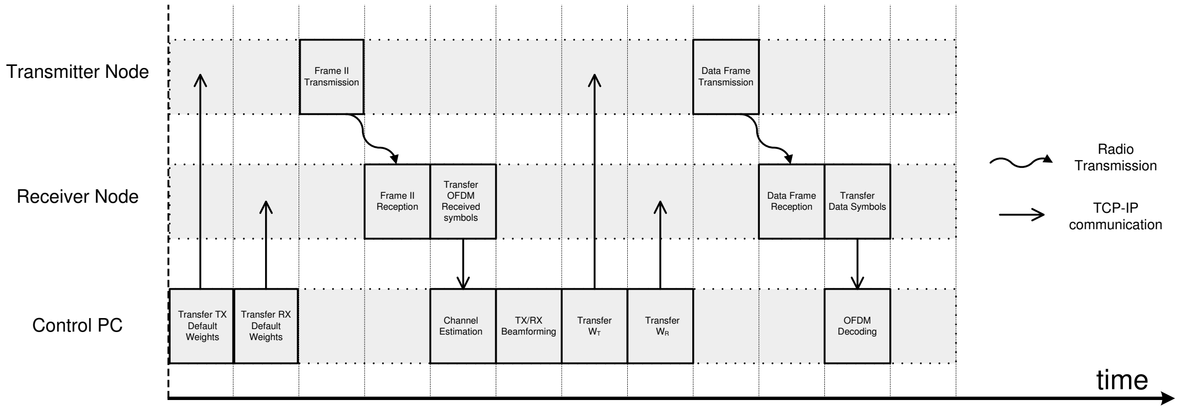


Figure 3: Temporal representation of the demonstration procedure

To implement RF domain combining philosophy it is necessary to estimate the MIMO channel. In order to do so, a new frame format has been introduced (see Figure 4), called training frame or MIMAX frame II, that differs from a 802.11a standard frame. In a 4×4 MIMO channel, it consists of 16 training symbols $(TW_1 \ldots TW_{16})$ that are transmitted/received using 16 combinations of Tx-Rx default weights. These weights must be chosen in order to estimate all the SISO channels between Tx-Rx antenna pairs. Due to weighting, this frame will be 802.11a incompatible and hence it will be discarded by 802.11a legacy devices.

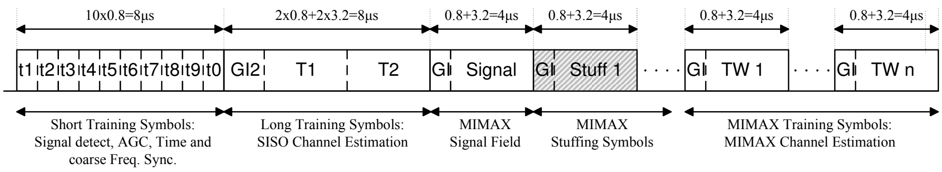


Figure 4: Training frame

First, the training frame is transmitted/received. Second, from channel estimates the optimal Tx/Rx weights are calculated according to a smartly chosen beamforming scheme. Concretely, results in Section 4 are obtained using a beamforming scheme denoted as *fixed Max-SNR* because it is a fixed point implementation that maximizes the signal to noise ratio at the receiver side. Other approaches are possible, such as minimizing the bit error rate or maximizing capacity [9].

Finally, one or multiple 802.11a standard frames are transmitted and received using any set of predefined/obtained weights. From the received signal and constellations, a series of performance parameters can be calculated and, as a result, a comparison among the different beamforming schemes can be carried out.

3.4 End-user graphical interface

A friendly end-user graphical interface has been developed to provide easy control and results visualization falling into outstanding results. By tuning input parameters such as transmission power, modulation order or beamformer weights one can observe the resulting RF-MIMO performance.

4 Results

There exist several results that can be obtained from the RF-MIMO demonstrator. On the one hand, channel measurements derived from the estimation of the channel can be obtained. This least-squares estimation is part of the training procedure described in Section 3.3 and allows wideband channel parameters to be extracted. Concretely, a measurement campaign has been conducted aiming at the indoor 5.6 GHz channel characterization. The measurement site is furnished with office equipments: tables, PCs and seats. Assuming a quasi-static environment, three representative Tx-Rx locations have been considered. These locations have been labeled as line-of-sight (LOS), non-line-of-sight (NLOS) and severe non line-of-sight (sNLOS) depending on the obstacles encountered in the Tx-Rx path. Besides, the distances between transmitter and receiver are 3.5, 12 and 18 meters respectively. It must be noticed that some antenna pairs may encounter NLOS channels in spite of being in a LOS location. This fact can lead to unexpected results, specially while obtaining indoor MIMO wideband parameters. Therefore, a nomadic channel characterization has been carried out by moving the receiver within a small local area (e.g., 900 cm2) and then averaging measurements in space.

MIMO channel frequency selectivity has been statically studied in terms of mean coherence bandwidth and mean delay spread. Obtained results are shown in Table 1.

Table 1: Wideband parameters measured at 5.6 GHz in an indoor office environment

	LOS	NLOS	sNLOS
Coherence bandwidth (MHz)	4.81	4.45	4.30
Delay spread (ns)	43.24	48.98	51.68

Effectively, coherence bandwidth decreases with the presence of scatterers in the transmission path, thus increasing the frequency selectivity of the channel. Obviously, the delay spread, that is inversely proportional to the coherence bandwidth, increases. Besides, measurement repeatability has corroborated channel time invariance.

On the other hand, performance results in terms of bit error rate (BER), error vector magnitude (EVM) and received power can also be available at the end of the procedure. These performance parameters are used to verify the improvements achieved by incorporating RF-MIMO features to conventional 802.11a systems. Concretely, a total of 10 measurements have been carried out for each location and SNR condition. Each measurement involves the transmission of 20 frames (each containing 2048 bits of data) using a $16QAM$ modulation with a coding rate of 3/4 (36 Mbps). The most representative results of this measurement campaign are shown in Table 2.

Transmission power difference between high SNR and low SNR cases is around 10 dB, but EVM values do not show the same difference because low SNR represents a noise-dominated case, while in high SNR other effects dominate. At most cases, RF-MIMO outperforms traditional SISO 802.11a. Specially, this occurs in severe NLOS locations and low SNR conditions where the channels are more frequency selective and communication is harder. Differences are reduced when a SISO channel dominates

Table 2: Comparison of studied combining strategies performance

Location	SNR condition / Scheme / Parameter	Low SNR SISO	Low SNR MIMO enhanced	High SNR SISO	High SNR MIMO enhanced
LOS	BER	$4.6 \cdot 10^{-2}$	$4.1 \cdot 10^{-3}$	$8.6 \cdot 10^{-3}$	$1.5 \cdot 10^{-2}$
	EVM	-16.65	-22.06	-19.05	-21.34
NLOS	BER	$3.4 \cdot 10^{-1}$	$1.25 \cdot 10^{-2}$	$7.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-3}$
	EVM	-8.40	-18.43	-16.39	-22.43
sNLOS	BER	$4.1 \cdot 10^{-1}$	$6.6 \cdot 10^{-2}$	$3.0 \cdot 10^{-1}$	$3.5 \cdot 10^{-2}$
	EVM	-4.92	-16.63	-8.74	-18.11

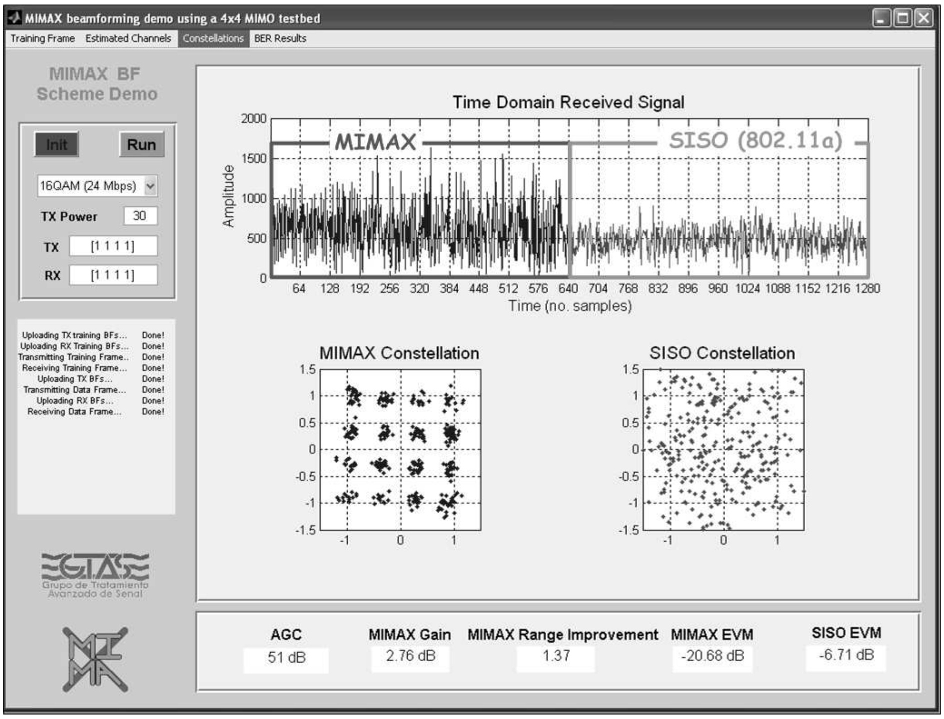


Figure 5: Graphical performance comparison between MIMAX & SISO

(LOS location) or noise is negligible (High SNR).

Moreover, the received time-domain signal along with the obtained constellations are shown in Figure 5. As can be easily seen, RF-MIMO (MIMAX) overcomes SISO (802.11a) in terms of received power and EVM. It is necessary to highlight that this power excess can be used to increase the transmission range, reduce BER, reduce power consumption, etc. In addition, when the transmitter focalize its power on certain receiver it is indirectly reducing the interference over the surrounding devices.

5 Conclusions

An RF-MIMO demonstrator has been developed in order to test the essential baseband processor components and the antenna array. Furthermore, the performance of the RF-MIMO concept has been successfully evaluated. The empirical results in this work have led us to corroborate the previously obtained theoretical and simulated results. Additionally, the 5 GHz band MIMO channel has been studied observing its time invariance and frequency selectivity. In short, the developed demonstrator and experimental evaluation have become a useful tool to assemble and evaluate components which belong to the MIMAX project partners.

Acknowledgments

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