# A FLEXIBLE TESTBED FOR THE RAPID PROTOTYPING OF MIMO BASEBAND MODULES

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**ABSTRACT**

Hardware platforms and testbeds are an essential tool to evaluate, in realistic scenarios, the performance of Multiple-Input-Multiple-Ouput (MIMO) systems. In this work we present a simple and easily reconfigurable $2 \times 2$ MIMO testbed for the rapid prototyping of the signal processing baseband functions. The signal generation module consists of a host PC equipped with a board that contains two high performance 100 MHz DACs and a 1 GB memory module that allows the transmission of extremely large frames of data. At the receiver side, we use another host PC equipped with two 105 MHz ADCs, another 1 GB memory module and a trigger that starts the acquisition process when the presence of signal is detected. The platform has been designed to operate at the ISM band of 2.4 GHz with a RF bandwidth of 20 MHz. In order to minimize the number of DAC and ADC circuits, signals are generated and acquired at an IF of 15 MHz. Upconversion to RF is performed with two RF vectorial signal generators (Agilent E4438C) and downconversion with two specific circuits designed from commercial components. Transmitter and receiver signal processing functions are implemented off-line in Matlab. To illustrate the performance and capabilities of the platform, we present the results of two experiments of a $2 \times 2$ MIMO transmission with Alamouti coding.

## 1. INTRODUCTION

The utilization of multiple antennas in both transmission and reception, referred to as Multiple-Input-Multiple-Output (MIMO) transmission systems, is one of the most promising technologies to achieve radio communication interfaces with a high spectral efficiency and reliability [1]. After years of extensive theoretical studies, different hardware MIMO testbeds have been developed [2–5] to assess the performance of MIMO coding, modulation and signal processing techniques in realistic scenarios.

In this paper we describe a flexible and easy-to-use $2 \times 2$ MIMO testbed, jointly developed at the Universities of Cantabria and A Coruña (SPAIN), which is intended for testing and rapid prototyping of MIMO baseband modules. A schematic diagram of the platform is shown in Fig. 1 and a picture of the system is shown in Fig. 2. Its basic operation is as follows: signal generation, modulation and space-time coding at transmission is carried out off-line using Matlab. The transmitting PC contains a board to generate the analog signals at an IF of 15 MHz. Since this board is equipped with a large (1 GB) and fast memory, the versatility of the platform is extremely high. The upconversion from the IF frequency of 15 MHz to the carrier RF frequency of 2.385 GHz is performed by two Agilent ESG E4438C signal generators and the signals are then transmitted through two printed dipole antennas.

At the receiver side, two downconverters translate the RF signal to the IF of 15 MHz. The downconverters have been specifically designed for this platform. The IF signals are acquired by the receive host PC using another board with two ADCs and a maximum sampling frequency of 105 MHz. Another fast and high capacity (1 GB) module is used to store the acquired signals. The memory content can be subsequently downloaded into the hard disk of the receiver host PC where synchronization, channel estimation, demodulation and decoding are performed off-line using Matlab.

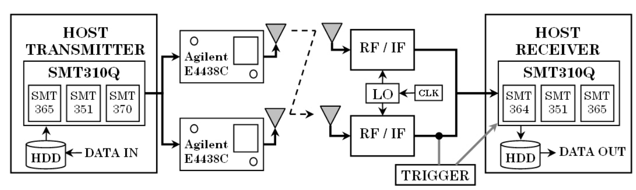


**Fig. 1**. Schematic diagram of the $2 \times 2$ MIMO platform.

In the following sections we describe with more detail the characteristics and capabilities of the baseband and RF subsystems that compose the platform. Finally, we discuss the results obtained from different MIMO transmissions using Alamouti space-time coding in two different indoor scenarios.

## 2. BASEBAND MODULES

### 2.1. IF signal generation

The transmitting host (see Fig. 1) uses a Sundance SMT310Q PCI board containing the following modules: an SMT365 (with the DSP TMS320C6416 from Texas Instruments and 16 MB of ZBTRAM (Zero Bus Turnaround RAM)), an SMT351 (1 GB of

This work has been supported by Xunta de Galicia, Ministerio de Educación y Ciencia of Spain and FEDER funds of the European Union under grants number PGIDT05PXIC10502PN, TEC2004-06451-C05-01 and TEC2004-06451-C05-02.

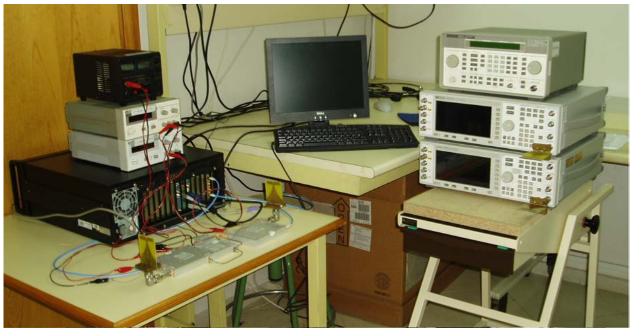

**Fig. 2**. A picture of the of the $2 \times 2$ MIMO platform.

DDR SDRAM FIFO memory), and an SMT370 (with two DACs AD9777 from Analog Devices). Data transmission between these modules is made through the Sundance High-Speed Bus (SHB) that works at the clock frequency of 100MHz and has a total width of 32 bits, i.e., the SHB provides an overall maximum transfer rate of 400 MB/s. The SHB is divided into two 16 bits Sundance Digital Buses (SDB) each of which is connected to one transmission channel. Thus, data is transferred from the memory to the DACs in a multiplexed mode at a maximum speed of 200 MB/s per channel. The transmitting process is controlled by the SMT365 module that contains a DSP at 600 MHz with 1 MB of internal memory. Besides this DSP, this module also contains:

- a Xilinx Virtex-II FPGA , that controls the FIFO queue and the SHB,
- a 16 MB ZBTRAM, working at 133 MHz and used to store the data before sending it to the 1 GB memory,
- and a Flash ROM of 8 MB that is used to store the initialization code of the DSP and to set the FPGA configuration data.

Inside the SMT310Q PCI board, control signals are carried by Comport buses (with a data rate of 20 MB/s). Triggers and clocks are linked using MMBX (Micro Miniature Board Connector) connectors. The storage module (SMT351) is able to save up to 1 GB of data at a speed of 400 MB/S, thanks to its 133 MHz DDR SDRAM and the SHB ports. Data sent by the DSP is saved in memory according to a FIFO policy, so the first incoming data will be the first data at the output. The management of this process is driven by a XilinxVirtex-II Pro X2VP7 FPGA. The SMT370 contains a dual AD9777 DAC with 16 bits of resolution and a maximum sampling frequency of 400 MHz with interpolation (100 MHz without interpolation). The module is controlled by a Xilinx Virtex-II FPGA and has two MMBX wired to male BNC connectors. These BNCs can be used to connect the board to the upconverters and/or other measurement devices (such as spectrum analyzers, oscilloscopes, etc...).

The operations of encoding, modulation and generation of the data files are made off-line in Matlab. The data files generated in this way are read and processed by the software of the DSP, which has been developed in C using the 3L Diamond API provided by Sundance. This software also performs:

- The configuration of the transmitter: adjustment of the two DACs, initialization of the communication ports, etc...
- The reading of data files from the hard disk.
- The data transmission through the SHB from the DSP to the 1 GB memory module. Later, this data will be sent from the memory module to the DAC.

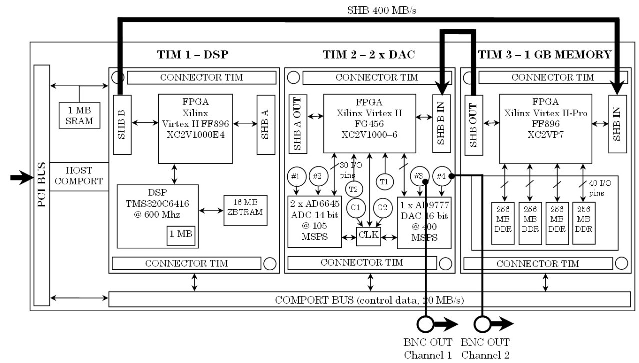


**Fig. 3**. Baseband TX board.

### 2.2. IF signal acquisition

To automate the process of transmitting and receiving data, we have designed an external trigger whose block diagram is shown in Fig. 4. This device monitors the signal power of one of the receiver channels. When its value exceeds a prefixed threshold, the trigger wakes up the ADCs of the receiver host. The advantages of using an external device to switch on the acquisition process are:

- The trigger is completely independent of the rest of the MIMO platform.
- The delay between transmitting and receiving data is limited to a few microseconds.
- The threshold can be easily graduated by means of an onboard microswitch.

The trigger is based on the power detector LTC5507 from Linear Technology. This integrated circuit accepts input signals between 1 KHz and 1 GHz, quantifies the power of the signal and sends a voltage level to the ADC of a LPC936 microcontroller (from Philips). The microcontroller monitors this voltage, and when it exceeds the prefixed threshold, it activates the two ADCs of the receiver host. The microcontroller software has been developed in C, with the Keil environment and using the LPC935 and LPC936 libraries.

Once the trigger activates the receiver ADCs, the capture starts. The IF signals are acquired by the receiver host PC using another Sundance SMT310Q board which contains the modules SMT365, SMT351 and SMT364 (with two dual ADCs AD6645 from Analog Devices). These ADCs have 14 bits of resolution and its maximum sampling frequency is 105 MHz. The difference with the transmitter hardware is just the use of this module with ADCs instead of the DACs module. The receiver software was also programmed in C using the 3L Diamond API. It is executed by the SMT365 DSP and performs hardware configuration and the tasks required to capture the data. The configuration comprises all the necessary steps to receive the data. Basically, these steps involve the allocation of receiving resources and the initialization of the ADCs parameters. The receiving memory is limited to the storage

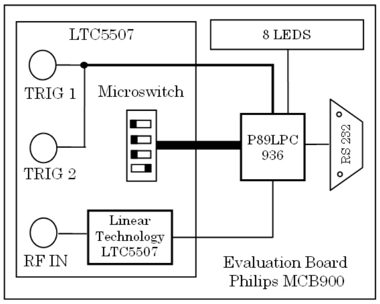


**Fig. 4**. Trigger components.

capacity of the SMT351 (1 GB). After filling the memory, the data is sent to the hard disk of the receiver host, where it will be off-line processed in Matlab.

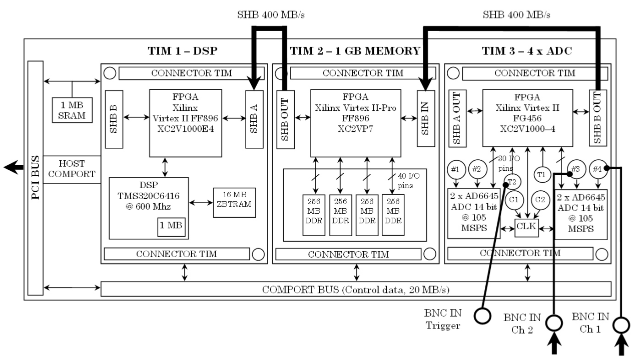

**Fig. 5**. Baseband RX board.

## 3. RF MODULES

The upconversion from the IF frequency of 15 MHz to the carrier RF frequency of 2.385 GHz is performed by two Agilent ESG E4438C signal generators and the signals are then transmitted through two printed dipole antennas. At this frequency, the transmitting power of the E4438C generators ranges between -136 dBm and 16 dBm.

On the other hand, it is important to notice that in order to use the signal generators merely as upconverters, they have to work with an I/Q modulation. However, the baseband module provides the analog signals at IF (in order to save one DAC per transmit antenna). A solution for this problem consists on using the IF signal to modulate the I branch, whereas the Q branch is disabled. The unwanted spectral replica generated in this way, which is located 30 MHz away (i.e., $2 \times f_{IF}$) from the signal of interest, will be filtered out by the downconverter.

Another important aspect of the upconversion stage for MIMO applications is the frequency synchronization of the two signal generators. In order to achieve frequency synchronization, both generators employ a common reference signal of 10 MHz. With this common reference we have measured a frequency offset between the generators that is below 10 Hz when the carrier frequency is 2.385 GHz. As we will see, this small frequency offset is not a problem because we employ less than 2 milliseconds to transmit a frame.

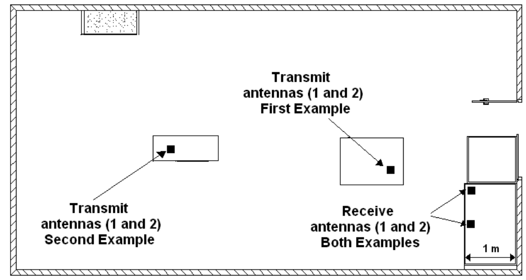


**Fig. 6**. Locations of the TX's and RX's in the two experiments.

At reception, two downconverters translate the RF signal to the IF of 15 MHz. The downconverters have been specifically designed for this platform and their main characteristics are the following: bandwidth of 20 MHz (2385 $\pm$10 MHz), gain of 50 dB, noise figure less than 2 dB, sensitivity of -88 dBm and output signal to noise ratio $> 10$ dB. The two downconverters employ a common local oscillator of frequency 2370 MHz, in this way there exists a perfect carrier frequency synchronism at the receiver side.

## 4. EXPERIMENTAL RESULTS

In order to illustrate the performance of the platform, we carried out two experiments using QPSK modulation and Alamouti space time coding [6]. The measurements were taken in the laboratory of the Signal Processing Group at the University of Cantabria. In the first experiment the transmitters and receivers were approximately three meters away from each other, with a clear line-of-sight (LOS) between them. In the second experiment the transmitters were located farther away from the transmitters ($\approx$ 10 meters) and the transmitting antennas were also moved to avoid a clear line-of-sight (see Fig. 6).

In both experiments the QPSK data were coded using the well-known Alamouti code [6]. Eq. (1) shows the space-time coding matrix where each row represents the symbols transmitted by each antenna and each column represents different time slots.

$$\mathbf{X} = \begin{pmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{pmatrix}. \tag{1}$$

Exploiting the orthogonality of the code and assuming that the channel matrix has been estimated using some training sequence, the maximum likelihood estimates of the transmitted symbols are given by

$$\hat{s}_1 = \sum_{j=1}^{n_R} h_{j1}^* r_1^j + h_{j2}(r_2^j)^* \tag{2a}$$

$$\hat{s}_2 = \sum_{j=1}^{n_R} h_{j2}^* r_1^j - h_{j1}(r_2^j)^* \tag{2b}$$

where $h_{ji}$ denotes the channel response between the $i$-th transmitting antenna and the $j$-th receiving antenna (the symbol rates considered in this experimental set-up yield a flat fading channel), and

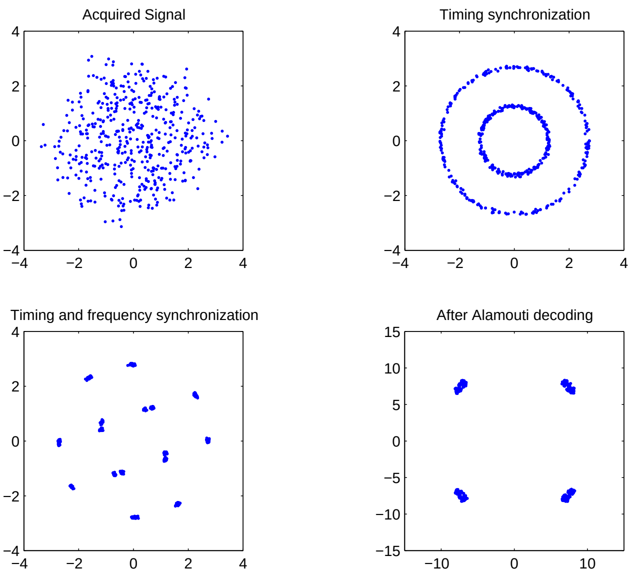


**Fig. 7**. Symbol constellations at the receiver.

$r_k^j$, $k = 1, 2$, denotes the $k$-th observation sampled at the symbol-rate at the $j$-th receiving antenna.

To simplify the symbol and frame synchronization tasks, we designed a frame structure composed of 63 symbols of preamble for frame synchronization, 256 pilot symbols for channel estimation, and 500 data symbols. In the preamble we use a pseudorandom sequence (PN) to facilitate frame synchronization and coarse symbol timing acquisition. Also, we use orthogonal pilots to simplify the channel estimation algorithm. Notice that this frame was selected to simplify the synchronization and estimation algorithms and not to maximize throughput.

Regarding the modulation parameters, the pulse shaping filter is a square-root raised cosine filter with a roll-off factor of 0.4. The symbol rate is 1 Mbaud, so the RF bandwidth is 1.4 MHz. The sampling frequency is 80 Msamples/sec. at both the transmitter and the receiver. This low symbol rate was used only for illustration purposes and in order to simplify the synchronization and channel estimation algorithms. There is no problem for the baseband hardware to achieve symbol rates up to 20 Mbaud. At the receiver, we perform carrier offset estimation and eliminate the carrier modulation. Afterwards, frame and symbol synchronization are carried out by exploiting the PN preamble. The final baseband observations are obtained through matched filtering and sampling at the symbol rate. Finally, a Least Squares (LS) estimate of the channel is calculated using the pilot symbols and the Alamouti decoding algorithm is applied.

Now we discuss the results obtained in the first scenario (close RX and TX antennas and clear LOS). Fig. 7 shows the signal received at one antenna (upper left), the signal after symbol timing (upper right), after carrier frequency offset and symbol timing (lower left) and after Alamouti decoding (lower right). In this example the transmitted power per antenna is -10 dBm.

We have repeated the experiment varying the transmitting power per antenna. For each transmitting power we repeated several times the experiment. Since the generation and coding at the transmitter side, and the demodulation, channel estimation and decoding at the receiver side are carried out off-line, the time between two consecutive trials is much larger that the coherence time of the channel. With this set-up we obtained the symbol error rate (SER) curve versus transmitting power, which is shown in Fig. 8.

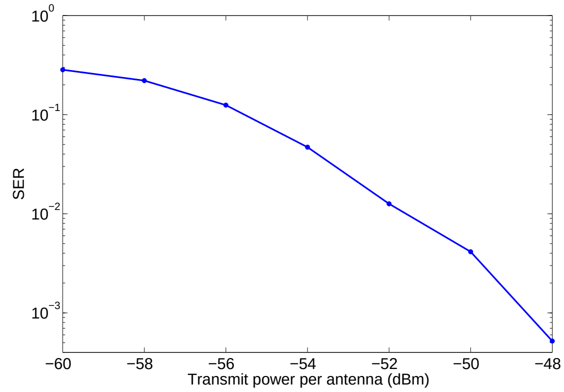


**Fig. 8**. SER for the first experiment.

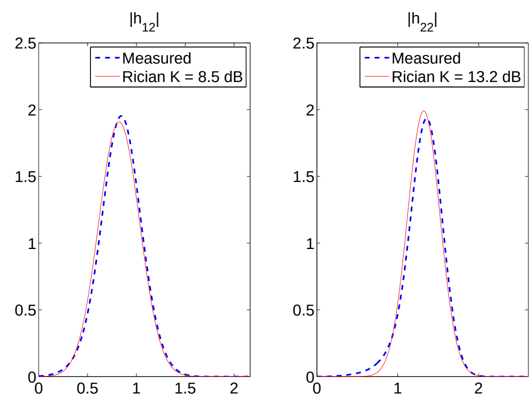


**Fig. 9**. PDF of two channel coefficients for the first experiment.

Additionally, we have studied the statistics of the channel for this particular location of the transmitting and receiving antennas. For each trial we have an estimate of the channel matrix obtained from the pilots. These different realizations of the flat-fading channel $h_{ij}$ allow us to estimate its probability density function (pdf) using, for instance, a Parzen estimator with a Gaussian kernel [7]. Not surprisingly, we have found that the channel for this experiment is clearly Ricean. To illustrate this point Fig. 9 shows the pdf of the estimated values of $|h_{12}|$ and $|h_{22}|$. For comparison, we have included in the figure the pdf of a Ricean distribution for the best matching Ricean factor $K$ (the parameter which measures the ratio between the power of the LOS and non-LOS components). The best matching Ricean factors are $K = 8{,}5$ dB for $|h_{12}|$ and $K = 13{,}2$ dB for $|h_{22}|$. Also, we can point out that the MIMO channel elements are neither independent (see (3)), nor identically distributed: all the elements follow a Ricean distribution but with very different $K$ factors. This can be attributed to the closeness be-

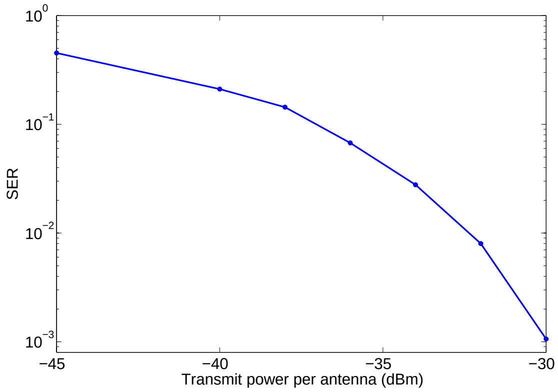


**Fig. 10**. SER for the second experiment.

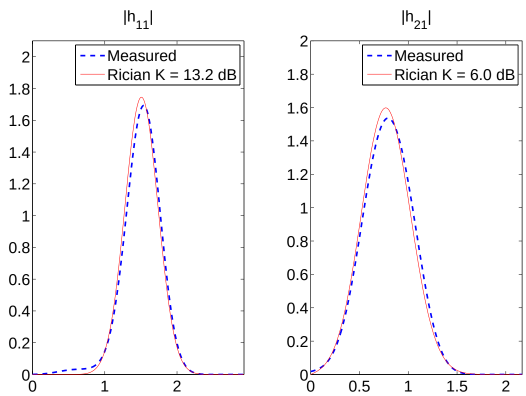


**Fig. 11**. PDF of two channel coefficients for the second experiment.

tween the two antennas at the transmitting and the receiving sites.

$$E\left\{vec\left(\mathbf{H}\right)vec\left(\mathbf{H}\right)^{H}\right\} = \begin{bmatrix} 1{,}0 & -0{,}2+0{,}7j & 0{,}5+0{,}3j & -0{,}8-1{,}0j \\ -0{,}2-0{,}7j & 0{,}7 & 0{,}1-0{,}5j & -0{,}6+0{,}9j \\ 0{,}5-0{,}3j & 0{,}1+0{,}5j & 0{,}4 & -0{,}8-0{,}2j \\ -0{,}8+1{,}0j & -0{,}6-0{,}9j & -0{,}8+0{,}2j & 1{,}7 \end{bmatrix} \quad (3)$$

Figures 10 and 11 show again the symbol error rate versus the transmitting power and some statistics of the measured channel. Although we have changed quite a lot the location of the transmitters, the channel remains Ricean. Now the best matching Ricean factors are $K = 13{,}2$ dB for $|h_{11}|$ and $K = 6$ dB for $|h_{21}|$. The main difference in comparison to the first experiment is that now we have to increase almost 15 dB the transmitting power of the RF signal generators to attain the same SER. A detailed discussion of these results is out of the scope of this paper.

## 5. CONCLUSIONS

In this paper we have shown a simple and flexible 2x2 MIMO platform that allows a fast prototyping of signal processing baseband modules. The system operates on the ISM band around 2.4 GHz with a maximum bandwidth of 20 MHz. The baseband transmission and reception is performed by two conventional PCs equipped with DACs, ADCs and memory, achieving a data transfer rate up to 200 MB/s per channel. The upconversion is carried out by two RF vectorial signal generators and the downconversion is done with two specific circuits designed from commercial components. The acquired signals are stored in the 1 GB DDR SDRAM memory and, later, they are processed off-line in Matlab. Such a way of working provides a fast and flexible evaluation of the baseband modules.

Eventually, to illustrate the platform performance, we have presented two experiments using QPSK modulation and Alamouti space time coding. Both experiments differ in the distance between the antennas of the transmitter and the receiver. The first experiment was located in a line-of-sight scenario where the transmitter was separated 3 meters from the receiver. On the other hand, in the second experiment the antennas were moved farther away (around 10 meters of distance) to avoid a clear line-of-sight. These experiments showed the good behavior of the 2x2 MIMO platform and enabled us to perform an statistical analysis of the indoor laboratory channel. In future work we will consider different indoor scenarios and we will present a detailed analysis of the results obtained with the MIMO platform.

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