Spatial correlation beamforming scheme for MISO channel emulation

Jesús Gutiérrez, Jesús Ibáñez and Jesús Pérez

Dept. of Communications Engineering, University of Cantabria
Santander, Spain 39005
Email: {jesusgt,jesus,jperez}@gtas.dicom.unican.es

***Abstract*—Temporal and spatial correlation are inherent mobile wireless channel characteristics that determine multiple-input multiple-output (MIMO) systems performance. Wireless test beds, which are developed to assess MIMO techniques under these realistic conditions, are usually placed in indoor laboratories where wireless channels are intrinsically quasi-static. In this paper we propose a methodology for emulating multiple-input single-output (MISO) channels with arbitrary distributions as well as spatial correlation characteristics. This methodology, based on time-varying beamforming, allow us to evaluate MISO techniques in controlled channel conditions. Moreover, it has been implemented and tested over a commercial MIMO test bed.**

I. INTRODUCTION

Spatial fading correlation is a crucial issue for practical multiple-input multiple-output (MIMO) wireless communication systems [1]. Both the link capacity and the performance of MIMO techniques are greatly affected by channels correlation characteristics [2].

MIMO test beds [3], [4], allow system tests and evaluations which are less expensive than field trials. However, realistic channel conditions are difficult to reproduce in low-mobility indoor scenarios where the test beds are usually placed. Measurements corroborate that, in indoor sites with the absence of motion within the environment, the channel response is time-invariant [5]. Wireless fading channel emulators [6], [7], [8] provide much more flexibility and reproduce accurate properties of actual propagation environments.

In this paper we propose a method, based on time-varying beamforming, to emulate narrowband multiple-input single-output (MISO) channels with any fading distribution as well as any spatial correlation characteristics. It allows us working under controlled and repeatable conditions that would not normally be possible in actual field testings. The methodology can be seen as an emulation of a block fading channel where the weights change from block to block, being fixed within a certain block. The method has been assessed for different channel distributions and spatial correlation matrices.

The remainder of the paper is organized as follows: Section II presents the proposed method for MISO channel emulation. The following steps towards its implementation on a certain equipment and the associated design issues are summarized in Section III. Section IV presents the validation of the method by simulation results and from measurements making use of a commercial wireless test bed. A comparison among simulation and measurement results is also included. Finally, Section V is devoted to the concluding remarks.

II. MISO SPATIAL EMULATION

A multiple-input single-output (MISO) system with n_T transmit antennas and one receive antenna, $n_R = 1$, is considered. Let $\mathbf{h} = \left[h_1 h_2 \ldots h_{nT}\right]^T$ represents the channel response, where h_i is the complex channel gain from the ith transmit antenna to the receive antenna, assumed known and time invariant, and $(\cdot)^T$ denotes transpose. A spatial-domain MISO beamforming scheme is depicted in Fig. 1. The transmit signals, $\mathbf{s} = [s_1 \; s_2 \; \ldots \; s_{n_T}]^T$, are multiplied by a transmit weight vector denoted as $\mathbf{w} = [w_1 \; w_2 \; \ldots \; w_{n_T}]^T$ ($\mathbf{w} \in \mathbb{C}^{n_T}$). In absence of noise, the output signal at the receiver, y, can be expressed as

$$y = \mathbf{s}^T diag\left(\mathbf{w}\right)\mathbf{h}, \tag{1}$$

where $diag\left(\mathbf{w}\right)$ denotes the diagonal matrix with diagonal terms equal to the elements in the vector $\mathbf{w}$. The MISO equivalent channel, $\mathbf{h}_e$, will be

$$\mathbf{h}_e = diag(\mathbf{w})\mathbf{h}. \tag{2}$$

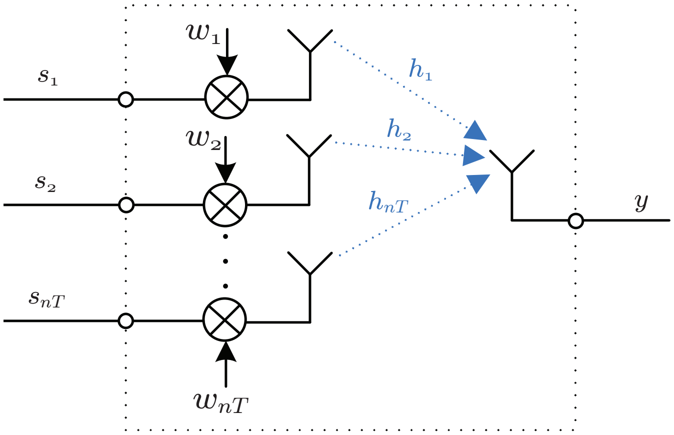

Fig. 1. MISO channel with complex weights at the transmitter.

The spatial correlation matrix of the equivalent channel can be expressed as

$$\mathbf{R} = E\left[\mathbf{h}_e\mathbf{h}_e^H\right] = E\begin{bmatrix} |h_1|^2|w_1|^2 & h_1h_2^*w_1w_2^* & \dots & h_1h_{n_T}^*w_1w_{n_T}^* \\ h_2h_1^*w_2w_1^* & |h_2|^2|w_2|^2 & \dots & h_2h_{n_T}^*w_2w_{n_T}^* \\ \vdots & \vdots & \ddots & \vdots \\ h_{n_T}h_1^*w_{n_T}w_1^* & h_{n_T}h_2^*w_{n_T}w_2^* & \dots & |h_{n_T}|^2|w_{n_T}|^2 \end{bmatrix}, \tag{3}$$

where $E[\cdot]$ is the expectation operator. Let suppose that we desire to emulate a MISO channel with the following complex spatial correlation matrix

$$\mathbf{R}_h^o = \begin{bmatrix} r_{11}^o & r_{12}^o & \dots & r_{1n_T}^o \\ r_{21}^o & r_{22}^o & \dots & r_{2n_T}^o \\ \vdots & \vdots & \ddots & \vdots \\ r_{n_T1}^o & r_{n_T2}^o & \dots & r_{n_Tn_T}^o \end{bmatrix}. \tag{4}$$

Then, from (3) and (4), the weights moments should be

$$E\left[w_iw_j^*\right] = \frac{r_{ij}^o}{h_ih_j^*}, \quad i,j = 1,\dots,n_T \tag{5}$$

Therefore, the weights correlation matrix will be

$$\mathbf{R}_w = E\left[\mathbf{w}\mathbf{w}^H\right] = \begin{bmatrix} \frac{r_{11}^o}{|h_1|^2} & \frac{r_{12}^o}{h_1h_2^*} & \dots & \frac{r_{1n_T}^o}{h_1h_{n_T}^*} \\ \frac{(r_{12}^o)^*}{h_2h_1^*} & \frac{r_{22}^o}{|h_2|^2} & \dots & \frac{r_{2n_T}^o}{h_2h_{n_T}^*} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\left(r_{1n_T}^o\right)^*}{h_{n_T}h_1^*} & \frac{\left(r_{2n_T}^o\right)^*}{h_{n_T}h_2^*} & \dots & \frac{r_{n_Tn_T}^o}{|h_{n_T}|^2} \end{bmatrix}. \tag{6}$$

According to (2), the weights distribution determines the distribution of the equivalent channel. If, for example, one desires to emulate a Rayleigh fading channel, the weights will be obtained from

$$\mathbf{w} = \mathbf{R}_w^{1/2}\mathbf{w}_w \sim CN(0,\mathbf{R}). \tag{7}$$

Vector $\mathbf{w}$ follows a zero-mean complex Gaussian distribution with covariance matrix $\mathbf{R}$, being $\mathbf{w}_w \sim CN(0,\mathbf{I}_{n_T})$, where $\mathbf{I}_{n_T}$ is the identity matrix of dimension n_T. From (7) we readily obtain realizations of the weights to emulate the desired Rayleigh fading channel with the spatial correlation matrix given by (4). Other expressions similar than (7) should be used for other fading distributions.

III. IMPLEMENTATION OF THE MISO CHANNEL EMULATOR

The first step regarding implementation leads us to decide where to fit our weighting methodology. Starting on the basis that we have a transmitter and a receiver device under test (DUT) and our aim is to emulate the MISO channel among them, weights application should be performed at the transmitter side. Since we want to apply the weights in a real-time context, we decided to implement the MISO methodology on the transmitter base band (BB) processor. Fig. 2 presents the general diagram of a typical implementation of our method.

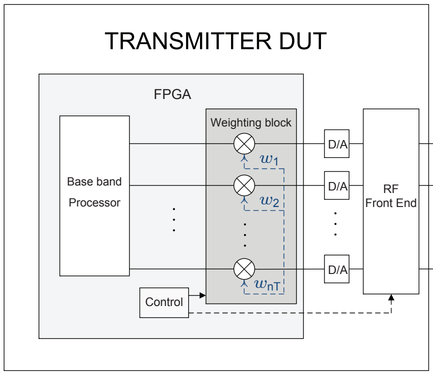

Fig. 2. MISO implementation scheme.

Basically, in terms of implementation, we add a new block called *Weighting Block* to the existing BB processor, allowing a sample-based weight delivering. It is in charge of applying the necessary weights to have a desired correlation among them with a certain distribution. The new block consists of n_T complex multipliers, each consisting of 4 multipliers and 2 adders. The baseband in-phase (I) and quadrature (Q) signal samples are generated by the base band (BB) processor and the weights are fed, along with the signal, to the complex multipliers. The outputs of the BB processor are converted to the analog domain by n_T dual digital to analog converters (D/A) and then upconverted by the radio frequency (RF) front end. The receiver simply just acquire the signals.

The weights are defined within the range $[-1,1]$ to ensure that if they are fixed to the maximum value, the IQ signals are not affected by saturation that can occur at the *Weighting Block* or at the D/A. If a higher dynamic range is desired, there exist a control that allows varying the transmit power amplifier (PA) gain at the RF Front End. It is important to take into account that the weights can be so small that the transmitted signal is received with low level and noisy. In this case, the receiver DUT should provide any kind of automatic gain control (AGC) to keep an adequate signal level.

The procedure starts from the assumption that the initial channel estimation has been previously carried out by the BB processor; otherwise, it can be carried out as described in Section IV. Since the channel response is considered time invariant, this initial estimation is considered during the experiment. The implementation of the proposed method relies on the common block fading assumption. During each channel state (block) the signals are transmitted with fixed weights and the equivalent channel remains constant within a block. From one state to another, the weights change according to a certain spatial correlation following any distribution.

IV. VALIDATION AND TEST

In this section we first validate the proposed method by means of simulation results. Then, it has been also implemented, working in real-time in our MIMO test bed [9]. Fig. 3 presents the configuration of the two test bed nodes, one acting as the transmitter and the other as the receiver. The

Weighting Block is fitted into the transmit field programmable gate array (FPGA) (Xilinx Virtex II). The DAC has 14 bits of resolution so the output of the *Weighting block* must be truncated to 14 bits. The transmit weight vector falls in the range $[-1, 1]$ with one bit for the sign and 15 bits for the decimal part.

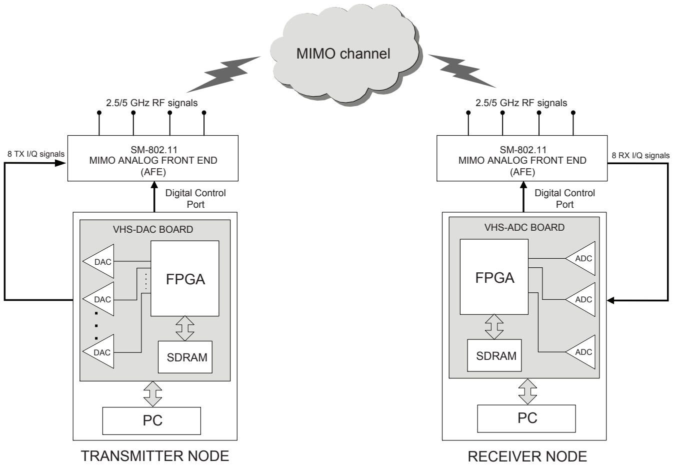

Fig. 3. Block diagram of the 4×4 MIMO test bed. (Left) Transmitter. (Right) Receiver.

Measurements were carried out at the R&D building of Telecommunications Engineering at the University of Cantabria. The transmitter was placed 4 meters away from the receiver. For the measurements used herein, the test bed had $n_T = 4$ and $n_R = 1$ transmit and receive antennas respectively using a uniform linear antenna array at the transmitter. It was operated with a carrier frequency of 5.6 GHz. Making use of the channel estimation methodology presented in [5], that has also been implemented in our test bed, we obtained the physical channel response, $\mathbf{h}$, fixing the weights value to one in order to bypass the *Weighting block*. Since there not exist any movement or people around the scenario, the channel can be considered time-invariant. We carried out this channel estimation 1000 times to prove the lack of variability (see Fig. 4). The last channel estimation was carried out 10 minutes later than the first one.

The measured magnitude of the MISO channel response was

$$|\mathbf{h}| = \begin{bmatrix} 0.8332 \\ 4.3886 \\ 2.3347 \\ 1.5531 \end{bmatrix} \tag{8}$$

and the phase

$$\arg(\mathbf{h}) = \begin{bmatrix} -161.8920 \\ -155.3734 \\ 175.2827 \\ 69.9333 \end{bmatrix}. \tag{9}$$

These channel estimates will serve us as starting point for both the simulation and the implementation results. Let assume

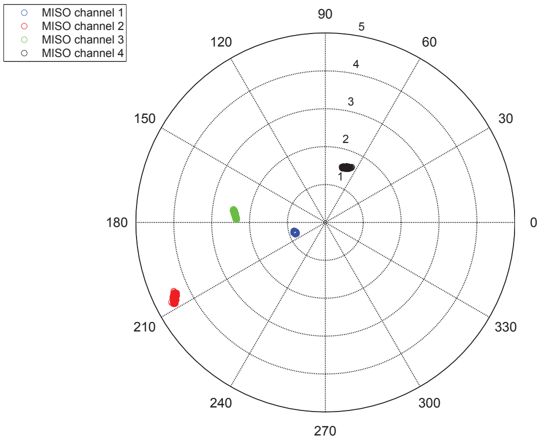

Fig. 4. MISO initial channel estimation with weights set to one, resulting time-invariant channels.

we desire to emulate a Rayleigh fading channel with the following spatial correlation values

$$|\mathbf{R}_h^o| = \begin{bmatrix} 0.2525 & 0 & 0.2517 & 0 \\ 0 & 0.2230 & 0.1267 & 0 \\ 0.2517 & 0.1267 & 0.4162 & 0 \\ 0 & 0 & 0 & 0.1083 \end{bmatrix} \tag{10}$$

$$\arg(\mathbf{R}_h^o) = \begin{bmatrix} 0 & 0 & -65.55 & 0 \\ 0 & 0 & 46.33 & 0 \\ 65.55 & -46.33 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

As can be seen from (10), there exist correlation among channels $1-3$ and $2-3$ being uncorrelated the rest of the combinations. Also, the channel 3 is the one that more gain provides. Once we obtain the weights realizations from (6) and (7), we get the equivalent channel according to (2). To estimate the correlation matrix we use the following expression

$$\mathbf{R}_h = \frac{1}{N}\sum_{1}^{N} \mathbf{h}_e \mathbf{h}_e^H. \tag{11}$$

where N is the number of weights realizations.

A. Simulation results

First, from (6) we computed the weights correlation matrix. Then, by using (7) we obtained $N = 10^6$ weight vector realizations. From them we obtain the equivalent channels according to (2) and we estimate the correlation matrix making use of (11), resulting

$$|\mathbf{R}_h^o| = \begin{bmatrix} 0.2526 & 0.0003 & 0.2519 & 0.0001 \\ 0.0003 & 0.2231 & 0.1267 & 0.0002 \\ 0.2519 & 0.1267 & 0.4162 & 0.0003 \\ 0.0001 & 0.0002 & 0.0003 & 0.1081 \end{bmatrix} \tag{12}$$

$$\arg(\mathbf{R}_h^o) = \begin{bmatrix} 0 & -12.47 & -65.46 & 174.47 \\ 12.47 & 0 & 46.28 & -101.19 \\ 65.46 & -46.28 & 0 & -143.03 \\ -174.47 & 101.19 & 143.03 & 0 \end{bmatrix}.$$

By comparing (10) and (12) we can verify the proper behavior of our method since the results match up very well with the desired correlation matrix. Obviously, the comparison among phase results whose elements are zero in the magnitude matrix are not of interest. Fig. 5 shows the histograms for the magnitudes of the entries of the equivalent channel, $\mathbf{h}e$.

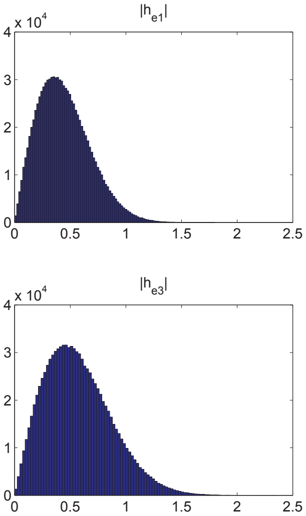

Fig. 5. Distributions of the 4×1 MISO channel (simulation).

B. Measurements

In this case, we just obtain $N = 1000$ weights realizations from (7), following a Rayleigh distribution. Then, making use of the channel estimation methodology presented in [5] we estimate, for all the realizations, the equivalent channel (consisting of the product of the channel itself and the weights). To that purpose, we transmit the signals multiplied by these weights from the transmitted node. The signals are sent through the channel and then received at the receiver node. For calculating the empirical correlation matrix from those equivalent channels we make use of (11). The estimated correlation matrix was

$$|\mathbf{R}_h| = \begin{bmatrix} 0.2374 & 0.0117 & 0.2513 & 0.0075 \\ 0.0117 & 0.2235 & 0.1441 & 0.0036 \\ 0.2513 & 0.1441 & 0.4379 & 0.0068 \\ 0.0075 & 0.0036 & 0.0068 & 0.1012 \end{bmatrix} \tag{13}$$

$$\arg(\mathbf{R}_h) = \begin{bmatrix} 0 & -76.65 & -64.55 & 142.28 \\ 76.65 & 0 & 43.05 & 154.23 \\ 64.55 & -43.05 & 0 & -160.30 \\ -142.28 & -154.23 & 160.30 & 0 \end{bmatrix}.$$

By comparing (13) and (12), we realize that the measurement results do not match very well with the simulated ones. Noise and impairments related to hardware can make the results worse. To verify this fact, we took those 1000 weights realizations and we calculate in Matlab the equivalent channel. Finally, we obtain the correlation matrix making use of (11).

$$|\mathbf{R}_h| = \begin{bmatrix} 0.2457 & 0.0133 & 0.2576 & 0.0071 \\ 0.0133 & 0.2190 & 0.1402 & 0.0034 \\ 0.2576 & 0.1402 & 0.4325 & 0.0078 \\ 0.0071 & 0.0034 & 0.0078 & 0.1028 \end{bmatrix} \tag{14}$$

$$\arg(\mathbf{R}_h) = \begin{bmatrix} 0 & -76.45 & -64.58 & 149.65 \\ 76.45 & 0 & 42.83 & 168.41 \\ 64.56 & -42.82 & 0 & -149.46 \\ -149.65 & -168.41 & 149.46 & 0 \end{bmatrix}.$$

As can be seen, (13) and (14) match very well. If we compare these results with those obtained by simulation we appreciate differences mostly caused by the number of realizations. This means that asymptotically all the results would match up.

On the other hand, we need to verify that the distributions of the equivalent channels follow the Rayleigh distribution. Fig. 6 shows the histograms for the magnitudes of the entries of the equivalent channel, h_{ei}.

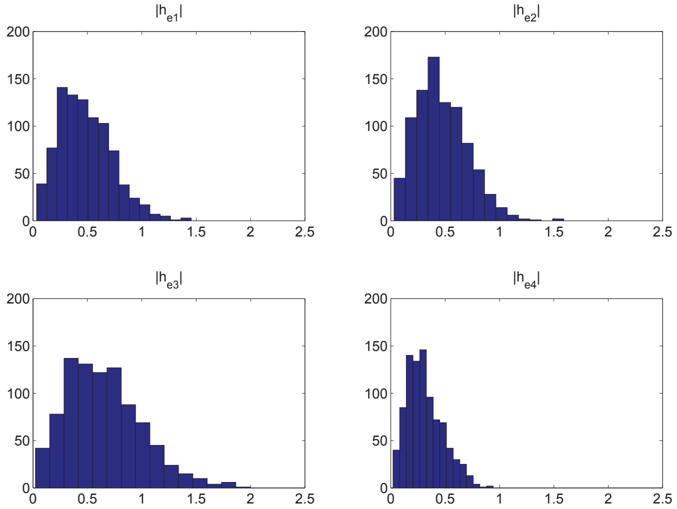

Fig. 6. Distributions of the 4×1 MISO channel (measurements).

V. CONCLUSIONS

A method to emulate narrowband MISO channels with certain spatial correlation and arbitrary distributions has been developed. It is based on time-varying beamforming and it can be seen as the emulation of a block fading channel varying according the weights given that the physical channel in fixed indoor environments is considered static. Therefore, it allows the evaluation of MISO algorithms under controlled and repeatable conditions. This is the first stage in order to tackle MIMO channel emulation controlling both spatial and temporal correlation, whose development is in progress, following the same principles as the ones presented in this paper.

VI. ACKNOWLEDGMENTS

This work has been supported by MICINN (Spanish Ministry for Science and Innovation) under grants TEC2010-19545-C04-03 (COSIMA) and CONSOLIDER-INGENIO 2010 CSD2008-00010 (COMONSENS). It also has been supported by FPI grant BES-2008-002085.

REFERENCES

[1] P. Kyritsi and D. Cox, "Correlation properties of mimo radio channels for indoor scenarios," in *Signals, Systems and Computers, 2001. Conference Record of the Thirty-Fifth Asilomar Conference on*, vol. 2, nov. 2001, pp. 994 –998 vol.2.

[2] D. shan Shiu, G. J. Foschini, M. J. Gans, J. M. Kahn, and S. Member, "Fading correlation and its effect on the capacity of multielement antenna systems," *IEEE Trans. Commun*, vol. 48, pp. 502–513, 2000.

[3] S. Caban, C. Mehlfhrer, R. Langwieser, A. L. Scholtz, and M. Rupp, "Vienna MIMO testbed," *EURASIP Journal on Applied Signal Processing, special issue on Implementation Aspects and Testbeds for MIMO systems*, 2006.

[4] A. G. i. Fábregas, M. Guillaud, D. T. M. Slock *et al.*, "A MIMO-OFDM Testbed for Wireless Local Area Networks," *EURASIP Journal on Applied Signal Processing*, vol. 2006, 2006.

[5] J. Gutiérrez, Ó. González, J. Pérez, D. Ramírez, L. Vielva, J. Ibáñez, and I. Santamaría, "Frequency-Domain Methodology for Measuring MIMO channels Using a Generic Test Bed," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 3, pp. 827–838, March 2011.

[6] T.-P. Wang, C.-H. Liao, and T.-D. Chiueh, "A Real-Time Digital Baseband MIMO Channel Emulation System," in *IEEE International Symposium on Circuits and Systems (ISCAS)*, May 2007, pp. 2606 –2609.

[7] T. Poutanen and J. Kolu, "Correlation Control in the Multichanne Fading Simulators," in *Vehicular Technology Conference, 2001. VTC 2001 Spring. IEEE VTS 53rd*, vol. 1, 2001, pp. 318 –322 vol.1.

[8] J. An and V.-J. Jung, "Implementation of MIMO Channel Simulator for SUI Channel Model Applications," in *Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on*, sept. 2007, pp. 1 –5.

[9] L. Vielva, J. Vía, J. Gutiérrez, Ó. González, J. Ibáñez, and I. Santamaría, "Building a web platform for learning advanced digital communications using a MIMO testbed," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2010)*, Dallas, USA, March 2010.