Performance of STBC transmissions with real data

José A. García-Naya
Tiago M. Fernández-Caramés
Héctor J. Pérez-Iglesias
Miguel González-López
and Luis Castedo
Dpt. Electrónica y Sistemas
Universidad de A Coruña
15071 A Coruña, SPAIN
E-mail: {jagarcia,tmfernandez,hperez,
mgonzalezlopez,luis}@udc.es

David Ramírez
Ignacio Santamaría
Jesús Pérez
and Javier Vía
Dpt. de Ingeniería de Comunicaciones
Universidad de Cantabria
39005 Santander, SPAIN
E-mail: {ramirezgd,nacho,jperez,
jvia}@gtas.dicom.unican.es

José M. Torres-Royo
IMS System Engineering
Motorola Inc.
28027 Madrid, SPAIN
E-mail: Jose.Miguel.Torres@motorola.com

***Abstract*— This paper presents a comparative study of three Space-Time Block Coding (STBC) techniques in realistic indoor scenarios. In particular, we focus on the Alamouti orthogonal scheme considering two types of Channel State Information (CSI) estimation: a conventional pilot-aided technique and a new blind method based on Second Order Statistics (SOS). We also considered a Differential (non-coherent) Space-Time Block code (DSTBC) that can be optimally decoded without CSI estimation, although it incurs in a 3 dB loss in performance. Experimental evaluation is carried out with a flexible and easy-to-use 2 × 2 MIMO platform at 2.4 GHz. Results show the excellent performance of the blind channel estimation technique in either Line-Of-Sight (LOS) and Non-LOS (NLOS) indoor scenarios.**

I. Introduction

Since the pioneering work of Foschini and Telatar [1], [2], multiple transmit and receive antennas have been used to drastically improve the performance of wireless communication systems. Specifically, since the work of Alamouti [3], and the later generalization by Tarokh *et al*. [4], space-time block coding (STBC) has emerged as one of the most promising techniques to exploit spatial diversity in Multiple-Input Multiple-Output (MIMO) systems.

Among space-time coding schemes, orthogonal space-time block coding (OSTBC) is one of the most attractive because it is able to provide full diversity gain without Channel State Information (CSI) at transmission and with very simple encoding and decoding procedures. The special structure of OSTBCs enables optimal Maximum Likelihood (ML) decoding using a simple linear receiver followed by a symbol-by-symbol detector.

The CSI required for coherent detection of OSTBCs is typically acquired by sending a training sequence that is known at the receiver side [5]. However, the price to be paid is reduced spectral efficiency, energy loss because training sequences do not carry any information and inaccurate channel estimates due to the effect of the noise and the limited number of training symbols.

Popular approaches to avoid the reduction on the spectral efficiency include the so-called Differential STBC (DSTBC) schemes [6]–[8] and Unitary Space-Time Modulation [9], [10]. These schemes do not require channel knowledge at the receiver but they incur in a performance penalty of 3 dB (differential coding) and 2–4 dB (unitary modulation) as compared to the coherent ML receiver [9]. Moreover, the receiver complexity for the unitary scheme increases exponentially with the number of points in the unitary space-time constellation.

In order to overcome the limitations of differential codes while, at the same time, avoiding the spectral efficiency reduction of pilot-aided techniques, several methods for blind channel estimation have been proposed [11], [12]. These methods can be divided into two groups depending on whether they exploit the higher-order statistics (HOS) or the second-order statistics (SOS) of the signals. HOS-based methods exhibit two major drawbacks: they present, in general, a higher computational cost and may require long streams of data to achieve accurate estimates. On the other hand, SOS-based methods are preferable in practice. Recently, a reduced-complexity SOS-based method for blind channel estimation under OSTBC transmissions has been proposed in [13]. Its performance has been evaluated by means of numerical examples, finding that in most cases it renders accurate channel estimates, provided that $n_R > 1$ receive antennas are available. However, for some OSTBCs (including Alamouti) some ambiguities appear that have to be avoided, for instance, using linear precoding at the transmitter or resorting to HOS.

In this paper, we focus on the evaluation of several of the above STBC transmission techniques over realistic indoor scenarios. To this end, we make use of a 2×2 MIMO testbed designed to operate at the 2.4 GHz Industrial, Scientific and Medical (ISM) band. Due to the limitations in the number of transmit antennas, we are constrained to the Alamouti code [3] and the differential STBC for two transmit antennas [6]. For Alamouti coherent decoding, we have employed a pilot-aided CSI estimation technique [5] and the blind technique proposed in [14], which avoids the indeterminacy problems of [13] by reducing in a few bits per second the transmission rate.

II. STBC AND DSTBC SCHEMES

Throughout this paper, we will consider a flat fading MIMO channel with n_T transmit and n_R receive antennas. This channel is conveniently represented as a matrix $\mathbf{H}$ of dimension $n_R \times n_T$, where each of the coefficients h_{ij} represents the complex transfer function between the jth transmitter to the ith receiver. The transmitted symbols are grouped in blocks of size M symbols and then encoded using a Space-Time Block Code (STBC) into the codeword matrix $\mathbf{S}[n]$ with dimension $n_T \times L$ where L is the codeword number of time slots. Notice that the transmission rate of this system is $R = M/L$.

After transmission through the MIMO channel, the nth block of received signals is represented with the $n_R \times L$ matrix

$$\mathbf{X}[n] = \mathbf{H}\mathbf{S}[n] + \mathbf{N}[n] \tag{1}$$

where $\mathbf{N}[n]$ is a $n_R \times L$ matrix representing the spatially and temporally Additive White Gaussian Noise (AWGN).

Assuming perfect knowledge of $\mathbf{H}$ and taking into account the Gaussian distribution of the noise, the coherent Maximum Likelihood (ML) decoding of $\mathbf{S}[n]$ is obtained after minimizing the following criterion [15]

$$\hat{\mathbf{S}}_{ML}[n] = \underset{\mathbf{S}[n]}{\text{argmin}} \, \|\mathbf{X}[n] - \mathbf{H}\mathbf{S}[n]\|^2, \tag{2}$$

subject to the constraint that the elements of $\hat{\mathbf{S}}[n]$ belong to a finite set $\mathcal{S}$. This is a NP-hard problem and optimal algorithms to solve it, such as *sphere decoding*, can be computationally expensive [16]–[18].

The complexity of the ML receiver reduces considerably when resorting to Orthogonal STBCs (OSTBC) in which the codeword matrices are orthogonal, i.e.,

$$\mathbf{S}[n]\mathbf{S}^H[n] = \mathbf{I}_{n_T} \tag{3}$$

where the superscript ^{H} denotes transpose conjugate and $\mathbf{I}_{n_T}$ is the $n_T \times n_T$ identity matrix. The ML decoding of OSTBCs is equivalent to M parallel symbol-by-symbol detection at the output of a linear receiver.

The most popular OSTBC is the Alamouti code [3], which transmits $M = 2$ complex symbols in $L = 2$ time slots (i.e., the code rate is $R = 1$). The codewords in the Alamouti code are constructed as

$$\mathbf{S}[n] = \begin{bmatrix} s_1[n] & -s_2^*[n] \\ s_2[n] & s_1^*[n] \end{bmatrix} \tag{4}$$

In this work we restrict ourselves to the Alamouti code because of the limitation in the number of transmitting antennas of the testbed used in the experiments. The use of a 2×2 platform limits the use of more sophisticated OSTBCs.

Coherent OSTBC decoding requires CSI knowledge at the receiver. This imposes practical constraints that can be avoided with the utilization of differential schemes. In our comparative study, we consider the Differential Space-Time Block Coding (DSTBC) for two transmit and two receive antennas described in [15]. This particular type of DSTBC is restricted to constant modulus signals. In this DSTBC scheme the transmitted codeword matrices ($\mathbf{Z}[n]$) are constructed as follows

$$\mathbf{Z}[n] = \mathbf{Z}[n-1]\mathbf{S}[n]$$

with $\mathbf{Z}[0] = \mathbf{I}_{n_T}$. When the matrices $\mathbf{S}[n]$ are the output of a OSTBC encoder, ML decoding of DSTBC reduces to M parallel symbol-by-symbol detection at the output of a linear receiver. The advantage of DSTBC is that decoding can be carried without the need of knowing the channel at the receiver. This advantage, however, is obtained at the expense of a 3 dB penalty in comparison with coherent detection.

III. CHANNEL ESTIMATION IN MIMO-OSTBC SYSTEMS

In this section we describe the channel estimation techniques used in the experiments for Alamouti decoding. Firstly, we consider the conventional pilot-based technique and, secondly, we describe a recently proposed blind technique.

A. Pilot-aided channel estimation

We have applied the channel estimation method described in [5]. Basically, we need to construct n_T orthogonal pilot sequences of size K.

$$\mathbf{S}^{\text{pilot}} = \begin{bmatrix} \mathbf{s}_1^{\text{pilot}} \\ \mathbf{s}_2^{\text{pilot}} \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & \dots & s_{1K} \\ s_{21} & s_{22} & \dots & s_{2K} \end{bmatrix} \tag{5}$$

The pilot sequences are designed to be orthogonal

$$\mathbf{s}_i^{\text{pilot}} \left(\mathbf{s}_l^{\text{pilot}}\right)^H \propto \delta_i^l$$

where δ_i^l is the Kronecker delta. This orthogonality among the pilot sequences allows us to independently estimate each fading coefficient h_{ij}. Specifically, the Minimum Mean Square Error (MMSE) estimate of h_{ij} is given by

$$\hat{h}_{ij} = \frac{\mathbf{x}_i^{\text{pilot}} \left(\mathbf{s}_j^{\text{pilot}}\right)^H}{\left\|\mathbf{s}_j^{\text{pilot}}\right\|^2} \tag{6}$$

where $\mathbf{x}_i^{\text{pilot}}$ is the received signal at the i-th antenna when $\mathbf{S}^{\text{pilot}}$ has been transmitted.

On the other hand, the transmission of a pilot sequence causes a reduction in the effective E_b/N_0 or, equivalently, a reduction in the effective transmission rate. For instance, if we transmit N_D data symbols and K pilots during the n-th frame, the transmitted rate associated to this technique is

$$R_{\text{pil}} = \frac{N_D}{N_D + K}.$$

B. SOS-based blind channel estimation

Recently, a new method for blind channel estimation under OSTBC transmissions has been proposed in [13]. It is based only on Second Order Statistics (SOS) and it is able to blindly identify the channel (up to a real scalar ambiguity) for most of the existing OSTBCs when the number of receive antennas is $n_R > 1$ [19]. However, some OSTBCs (including the Alamouti code used in this paper) cannot be identified by this method due to an additional ambiguity, which must

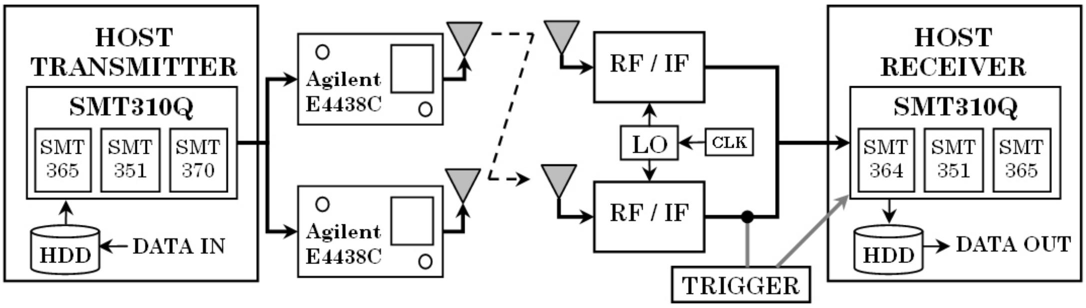

Fig. 1. Schematic diagram of the 2×2 MIMO platform.

be eliminated by resorting to other information (e.g., linear precoding, non-white source signals, reduced rate, etc.) [13]

In this paper we use a particularly simple method which has been recently proposed in [14]. There, it was proved that any OSTBC transmitting an odd number of real symbols, M', is identifiable regardless of the number of receiving antennas. The number of real symbols, M', in a OSTBC codeword is

$$M' = \begin{cases} M & \text{for real constellations,} \\ 2M & \text{for complex constellations.} \end{cases} \qquad (7)$$

Therefore, any non-identifiable complex OSTBC can be made identifiable simply by not transmitting one real symbol per OSTBC block. Obviously the transmission rate is reduced, but this rate penalty can be controlled by eliminating only one real symbol each time B OSTBC codewords are transmitted. In this case, the transmission rate is

$$R_{\text{blind}} = \frac{BM' - 1}{BM'} \qquad (8)$$

which tends to one for $B \gg 1$. Obviously, there is a trade-off between the quality of the channel estimate and R_{blind} as a function of B. This issue has been discussed in [14].

IV. MIMO TESTBED

In the results that follow, we examine the performance of STBC schemes in realistic scenarios using real data from indoor environments. The real data was obtained using a flexible and easy-to-use 2×2 MIMO testbed, jointly built at the Universities of Cantabria and A Coruña (Spain). This MIMO testbed 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 are 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 IF 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 specifically designed for this platform translate the RF signal to IF. The IF signals are acquired by the receive host PC using another board with two ADCs with a maximum sampling frequency of 105 MHz. Another fast and high capacity (1 GB) memory 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®. See [20] for a detailed description of the MIMO platform.

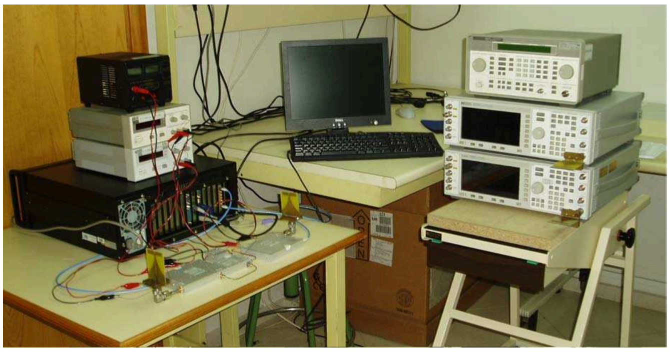

Fig. 2. A picture of the 2×2 MIMO platform.

V. EXPERIMENTAL RESULTS

In this section we compare the performance of the Alamouti scheme for pilot aided channel estimation, blind channel estimation and the Differential STBC that we have described in sections II and III. 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 two meters away from each other, with a clear Line-Of-Sight (LOS) between them. In the second experiment, the receivers were located farther away from the transmitters (≈ 10 meters) and the transmitting antennas were also moved to avoid a clear line-of-sight (see Fig. 3).

To simplify symbol and frame synchronization, we designed a frame structure composed of 63 preamble symbols for frame synchronization, up to 64 pilot symbols for channel estimation (for pilot-aided techniques) and 1000 data symbols (see Fig. 4). In the preamble we use a pseudorandom sequence (PN) to facilitate frame synchronization and coarse symbol timing acquisition. Notice that this frame was selected to simplify

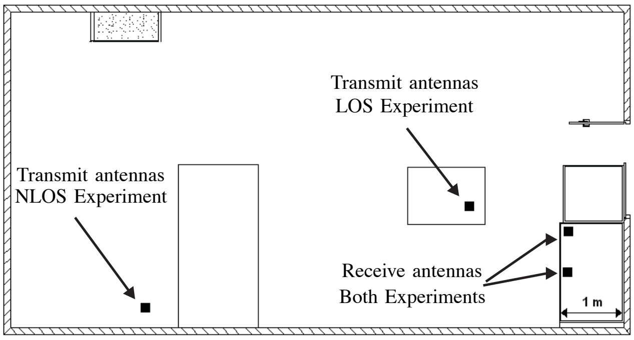

Fig. 3. Locations of the TX's and RX's in the two experiments.

the synchronization and estimation algorithms and not to maximize throughput.

Regarding the modulation parameters, we employ a QPSK modulation. 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 high sampling rate was used to simplify the synchronization algorithms. 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.

Preamble (63)	Pilots (64)	Information (1000)

Fig. 4. Frame structure chosen for the experiments.

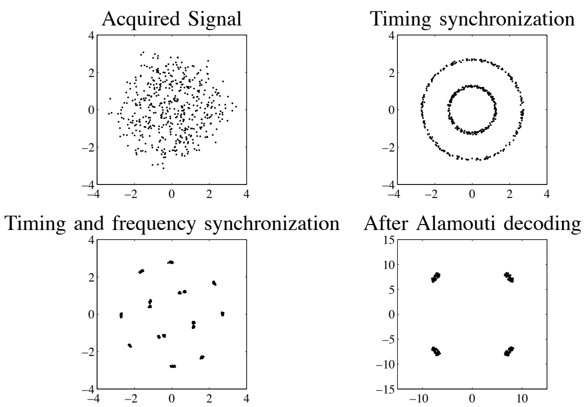

Fig. 5. Symbol constellations at the receiver.

Fig. 5 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 the first scenario (close RX and TX antennas and clear LOS) when the transmitted power per antenna is -10 dBm.

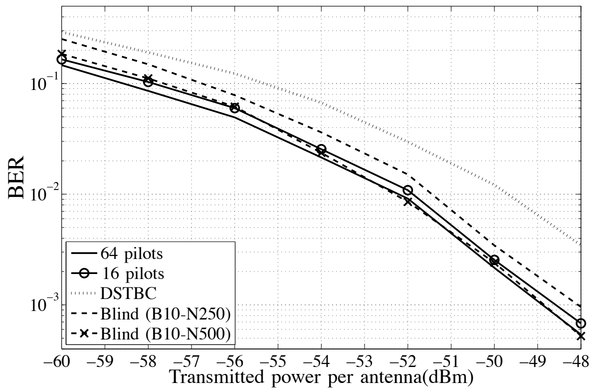

Fig. 6. BER for the LOS scenario.

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 bit error rate (BER) curve versus transmitting power shown in Fig. 6. In this figure we compare:

- The Alamouti OSTBC with pilot-aided channel estimation (labeled as K pilots)
- The Alamouti OSTBC with blind channel estimation, labeled as Blind (BX-NY), where X is the number of Alamouti blocks in which we eliminate one real symbol (to avoid the ambiguity) and Y is the number of blocks that we use to estimate the correlation matrix.
- The DSTBC.

Tab. I shows the corresponding rates for the considered Alamouti transmissions.

Method	Rate
64 Pilots	0.9398
16 Pilots	0.9843
Blind (B10-N250)	0,9750
Blind (B10-N500)	0,9750

TABLE I

RATE FOR THE DIFFERENT CHANNEL ESTIMATION METHODS.

As we can see from Fig. 6 and Table I, the blind technique with $N = 500$ blocks practically achieves the same performance as the pilot-aided method with 64 pilots, but transmitting at a higher rate. This improvement is achieved at the expense of a moderate increase of the computational cost, since the blind technique has to obtain the main eigenvector of a 8×8 correlation matrix. On the other hand, we also observe the expected 3 dB loss for the DSTBC and that the pilot-aided method with 16 pilots losses about 0.4 dB with respect to the utilization of 64 pilots. Using more than 64 pilots is not necessary because it does not improve system performance.

Finally, if we use less blocks for channel estimation in the blind technique, the estimate of the correlation matrix is worst and this causes a loss in BER. Specifically, if we use $N = 250$ instead of $N = 500$ blocks, the loss is about 0.9 dB. However, the use of a reduced number of blocks for blind channel estimation permits the use of shorter frames, which is especially important when the channel coherence time is smaller.

Figure 7 shows again the BER versus the transmitting power for the different methods in a NLOS scenario. The main difference with respect to the first experiment is that now we have to increase almost 27 dB the transmitting power of the RF signal generators to attain the same BER, but the comparison among the different STBC transmission leads to similar conclusions in this new scenario.

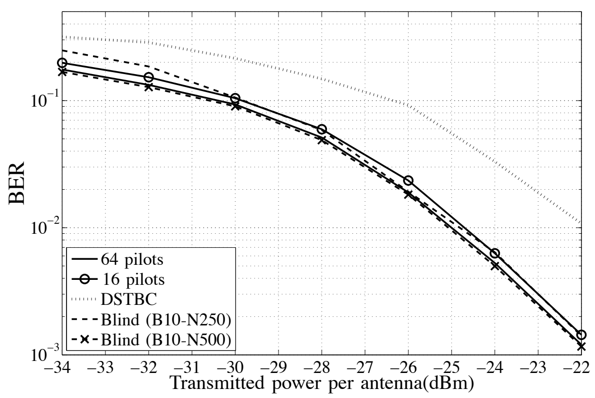

Fig. 7. BER for the NLOS scenario.

VI. Conclusions

In this paper we have compared the performance of several STBC systems on real data obtained from indoor scenarios using a 2×2 MIMO platform at 2,4 GHz. In particular, we have compared the Alamouti orthogonal scheme with coherent and non-coherent demodulation. The channel was estimated using two different methods: a conventional pilot-aided technique and a recently proposed blind algorithm based on SOS. In both LOS and NLOS scenarios, the blind channel estimation technique provides similar BER performance than the pilot-aided method, with a slight increase in the effective data rate and a moderate increase in the computational complexity of the detector. On the other hand, the differential STBC presents, as expected, a 3-dB penalty in comparison with coherent schemes, but it can be of interest due to its simplicity and its potential advantages in rapidly time-varying channels.

Acknowledgment

This work has been supported by Ministerio de Educación y Ciencia of Spain, Xunta de Galicia and FEDER funds of the European Union under grants number TEC2004-06451-C05-02, TEC2004-06451-C05-01, PGIDT05PXIC10502PN and FPU grant AP2004-5127.

References

[1] G. Foschini and M. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, pp. 311–335, 1998.

[2] I. E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. on Telecommunications*, vol. 10, no. 6, pp. 585–595, Nov.-Dec. 1999.

[3] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Comm.*, vol. 45, no. 9, pp. 1451–1458, 1998.

[4] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-Time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.

[5] A. F. Naguib, V. Tarokh, N. Seshadri, and A. R. Calderbank, "A space-time coding modem for high-data-rate wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1459–1478, Oct. 1998.

[6] V. Tarokh and H. Jafarkhani, "A differential detection scheme for transmit diversity," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 7, pp. 1169–1174, Jul. 2000.

[7] B. L. Hughes, "Differential Space-Time modulation," *IEEE Transactions on Information Theory*, vol. 46, no. 7, pp. 2567–2578, Nov 2000.

[8] B. Hochwald and W. Sweldens, "Differential Unitary Space-Time Modulation," *IEEE Transactions on Communications*, pp. 2041–2052, Dec. 2000.

[9] B. Hochwald and T. Marzetta, "Unitary space-time modulation for multiple-antenna communications in rayleigh flat fading," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 543–564, Mar. 2000.

[10] B. Hochwald, T. Marzetta, T. Richardson, W. Sweldens, and R. Urbanke, "Systematic Design of Unitary Space-Time Constellations," *IEEE Trans. Inform. Theory*, vol. 46, no. 6, pp. 1962–1973, 2000.

[11] C. Budianu and L. Tong, "Channel estimation for Space-Time Orthogonal Block Codes," *IEEE Transactions on Signal Processing*, vol. 50, no. 10, pp. 2515–2528, Oct. 2002.

[12] P. Stoica and G. Ganesan, "Space-Time block codes: Trained, blind, and semi–blind detection," *Digital Signal Processing*, vol. 13, pp. 93–105, Jan. 2003.

[13] S. Shahbazpanahi, A. B. Gershman, and J. H. Manton, "Closed-form blind MIMO channel estimation for orthogonal space-time block codes," *IEEE Trans. Signal Processing*, vol. 53, no. 12, pp. 4506–4517, Dec. 2005.

[14] J. Vía, I. Santamaría, and J. Pérez, "A Sufficient Condition for Blind Identifiability of MIMO-OSTBC Channels Based on Second Order Statistics," in *Seventh IEEE Workshop on Signal Processing Advances in Wireless Communications*, Cannes, France, July 2006.

[15] E. G. Larsson, P. Stoica, and G. Ganesan, *Space-Time Block Coding for Wireless Communications*. New York, USA: Cambridge University Press, 2003.

[16] U. Fincke and M. Pohst, "Improved methods for calculating vectors of short length in a lattice, including a complexity analysis," *Mathematics of Computation*, vol. 44, pp. 463–471, Apr. 1985.

[17] O. Damen, A. Chkeif, and J. Belfiore, "Lattice code decoder for space-time codes," *IEEE Comm. Lett.*, vol. 4, no. 5, pp. 161–163, May 2000.

[18] J. Jaldén, C. Martin, and B. Ottersten, "Semidefinite Programming for Detection in Linear Systems – Optimality Conditions and Space-Time Decoding," in *IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 4, April 2003, pp. 9–12.

[19] J. Vía and I. Santamaría, "On the Blind Identifiability of Orthogonal Space-Time Block Codes from Second Order Statistics," *Submitted to IEEE Transactions On Information Theory*.

[20] D. Ramírez and *et al*, "A flexible testbed for the rapid prototyping of MIMO baseband modules," in *3rd International Symposium on Wireless Communication Systems*, Valencia, Spain, September 2006.