A BLIND CHANNEL ESTIMATION STRATEGY FOR THE 2X1 ALAMOUTI SYSTEM BASED ON DIAGONALISING 4TH-ORDER CUMULANT MATRICES

Héctor J. Pérez-Iglesias, José A. García-Naya, Adriana Dapena

Departamento de Electrónica y Sistemas
Universidade da Coruña, Facultad de Informática
Campus de Elviña, 5
15071, A Coruña, Spain
e-mail: {hperez,jagarcia,adriana}@udc.es

ABSTRACT

This paper presents a novel blind strategy to estimate the channel parameters in systems that make use of the well known Alamouti orthogonal space-time code to achieve full diversity. The channel parameters are obtained by computing the eigenvectors of a matrix containing 4th-order cumulants of the observations. The matrix to diagonalise is selected for each channel realization using a simple criterion based on the spread of its eigenvalues. Simulation results show that the performance of the proposed method is similar to the obtained using the well-known joint approximate diagonalisation of eigenmatrices (JADE) algorithm, with a low computational cost.

***Index Terms*—** MIMO systems, Channel coding, Decoding.

1. INTRODUCTION

In the last decade, a large number of Space-Time Coding (STC) techniques have been proposed in the literature to exploit spatial diversity in systems with multiple elements at both transmission and reception (see, for instance, [1, 2] and references therein). A remarkable example is the Orthogonal Space Time Block Coding (O-STBC) because it is able to provide full diversity gain with linear decoding complexity [3, 4]. The basic premise of O-STBC is the encoding of the transmitting symbols into an unitary matrix to spatially decouple their Maximum Likelihood (ML) detection, which can be seen as a Matched Filter (MF) followed by a symbol-by-symbol detector.

In addressing the issue of decoding complexity, Alamouti has proposed in [3] an O-STBC scheme for transmission in systems with two antennas at the transmitter and only one at the receiver (see Figure 1). Each pair of symbols $\{s_1, s_2\}$ is transmitted in two adjacent periods using a simple strategy: in the first period s_1 and s_2 are transmitted from the first and the second antenna, respectively, and in the second period, $-s_2^*$ is transmitted from the first antenna and s_1^* from the second one. In this paper, we will consider that the exact probability density function of s_i is unknown. We also assume that they are complex-valued, zero-mean, stationary, non-Gaussian distributed, statistically independent and have the same kurtosis.

The transmitted symbols (sources) arrive at the receiving antenna through the fading paths h_1 and h_2, i.e., the signal received

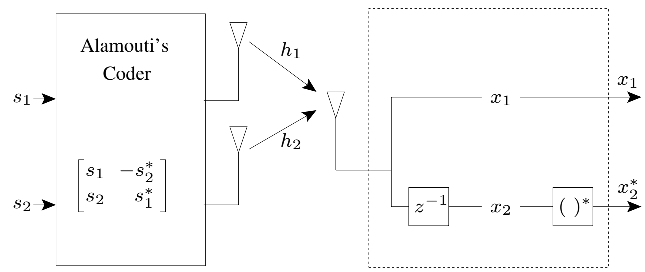

Fig. 1. Alamouti coding scheme

in the two adjacent periods have the form

$$
\begin{aligned}
x_1 &= s_1\, h_1 + s_2\, h_2 + n_1 \\
x_2 &= s_1^*\, h_2 - s_2^*\, h_1 + n_2
\end{aligned} \tag{1}
$$

where n_i is additive white Gaussian noise. The observation vector $\mathbf{x} = [x_1\ x_2^*]^T$ can be interpreted as an instantaneous mixture of the transmitted symbols given by

$$\mathbf{x} = \mathbf{H}\,\mathbf{s} + \mathbf{n} \tag{2}$$

where $\mathbf{s} = [s_1\ s_2]^T$ is the source vector, $\mathbf{n} = [n_1\ n_2^*]^T$ is the noise vector and $\mathbf{H}$ is the 2×2 channel matrix,

$$\mathbf{H} = \left[\begin{array}{cc} h_1 & h_2 \\ h_2^* & -h_1^* \end{array} \right] \tag{3}$$

It is interesting to note that $\mathbf{H}$ is an orthogonal matrix, $\mathbf{H}\,\mathbf{H}^H = \mathbf{H}^H\,\mathbf{H} = ||\mathbf{h}||^2\,\mathbf{I}_2$ where $||\mathbf{h}||^2 = |h_1|^2 + |h_2|^2$ is the squared Euclidean norm, $\mathbf{I}_2$ is the 2×2 identity matrix and ^{H} is the Hermitian operator. As a result, the transmitted symbols can be recovered using $\hat{\mathbf{s}} = \mathbf{H}^H\,\mathbf{x}$.

The performance of system with the Alamouti coding scheme, as most other coding strategies, depends on the accurate estimation of the matrix channel $\mathbf{H}$. The transmission of pilot symbols, referred to as training symbols, is often used to perform channel estimation required for a coherent detection of O-STBCs [5, 6]. However, training symbols reduce the throughput and such schemes are inadequate when the bandwidth is scarce. Recently, it has been proposed several strategies to avoid this limitations. One of the more popular is the called Differential STBC (DSTBC) [7]. The price to paid is a penalty of 3 dB as compared to the coherent ML receiver.

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 and TEC2004-06451-C05-01.

Another class of methods to estimate the channel matrix consists in using Blind Source Separation (BSS). In particular, this paper focuses on higher-order eigen-based approaches like the popular method Joint Approximate Diagonalization of Eigenmatrices (JADE) [8]. This algorithm provides excellent results but presents a high computational load because several 4th-order cumulant [9] matrices are simultaneously diagonalised. Recently, it has been proposed other higher-order eigen-based approaches for the particular case of systems with O-STBC [10, 11]. The channel matrix is estimated by performing only a 4th-order cumulant matrix eigenvalue decomposition. Unfortunately, although this approaches have a reduced computational cost, their performance is considerably degraded for high SNRs.

In this paper we will show that the performance of eigen-based approaches, like the presented in [10, 11], depends on the eigenvalue spread. Using this result, in Section 2 we will propose a novel strategy to estimate the channel matrix from only one 4th-order cumulant matrix. Simulation results will be presented in Section 3. Finally, Section 4 is devoted to the conclusions.

2. CHANNEL ESTIMATION USING 4TH-ORDER CUMULANTS

2.1. Definitions

Let us start by defining the 4th-order cumulant matrix as

$$\begin{aligned} \mathbf{C}[k,l] &= c_4(\mathbf{x}, \mathbf{x}^H, x_k, x_l^*) \\ &= \begin{bmatrix} c_4(x_1, x_1^*, x_k, x_l^*) & c_4(x_1, x_2^*, x_k, x_l^*) \\ c_4(x_2, x_1^*, x_k, x_l^*) & c_4(x_2, x_2^*, x_k, x_l^*) \end{bmatrix} \end{aligned} \quad (4)$$

where the indices k, l denote time-slots ($k, l \in \{1, 2\}$ for the Alamouti scheme) and the cumulant $c_4(x_1, x_2, x_3, x_4)$ is obtained from the 2nd- and the 4th-order moments of the observations, it is

$$\begin{aligned} c_4(x_1, x_2, x_3, x_4) &= E[x_1x_2x_3x_4] - E[x_1x_2]E[x_3x_4] \quad (5) \\ &- E[x_1x_3]E[x_2x_4] - E[x_1x_4]E[x_2x_3] \end{aligned}$$

Considering equation (2), in the appendix we show that these matrices can be rewritten as

$$\mathbf{C}[k,l] = c_4(\mathbf{x}, \mathbf{x}^H, x_k, x_l^*) = \rho_4 \cdot \mathbf{H} \cdot \mathbf{\Delta}[k,l] \cdot \mathbf{H}^H \quad (6)$$

where $\rho_4 = c_4(s_1, s_1^*, s_1, s_1^*) = c_4(s_2, s_2^*, s_2, s_2^*)$ is the kurtosis of the sources, and $\mathbf{\Delta}[k,l] = diag(\delta_1, \delta_2)$ is a diagonal matrix. In other words, the 4th-order cumulant matrices have the form

$$\begin{aligned} \mathbf{C}[k,l] &= \rho_4 \cdot \mathbf{H} \cdot \mathbf{\Delta}[k,l] \cdot \mathbf{H}^H \\ &= \rho_4 \cdot \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \cdot \begin{bmatrix} \delta_1 & 0 \\ 0 & \delta_2 \end{bmatrix} \cdot \begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix} \\ &= \rho_4 \cdot \begin{bmatrix} \delta_1|h_1|^2 + \delta_2|h_2|^2 & (\delta_1 - \delta_2)h_1h_2 \\ (\delta_1 - \delta_2)(h_1h_2)^* & \delta_1|h_2|^2 + \delta_2|h_1|^2 \end{bmatrix} \end{aligned} \quad (7)$$

In particular, the matrix $\mathbf{C}[1,1]$ is obtained when $\delta_1 = |h_1|^2$ and $\delta_2 = |h_2|^2$, matrix $\mathbf{C}[2,2]$ corresponds to $\delta_1 = |h_2|^2$ and $\delta_2 = |h_1|^2$ and $\mathbf{C}[1,2]$ corresponds to $\delta_1 = h_1h_2$ and $\delta_2 = -h_1h_2$. Furthermore, a linear combinations of matrices $\mathbf{C}[k,l], \; k,l = 1,2$ also can be written as equation (6).

2.2. Eigenvalue decomposition

Let $\mathbf{C}[k,l]^{i,j}$ be the elements into the i-th row, j-th column of matrix $\mathbf{C}[k,l]$. The general method to compute the eigenvalues of $\mathbf{C}[k,l]$ is

$$\lambda_i = \frac{t \pm \sqrt{t^2 + 4d}}{2}, \;\; i = 1, 2 \quad (8)$$

where $t = \mathbf{C}[k,l]^{1,1} + \mathbf{C}[k,l]^{2,2}$ and $d = \mathbf{C}[k,l]^{2,1}\mathbf{C}[k,l]^{1,2} - \mathbf{C}[k,l]^{1,1}\mathbf{C}[k,l]^{2,2}$. The corresponding eigenvectors are

$$\mathbf{u}'_i = \begin{bmatrix} \frac{\mathbf{C}[k,l]^{1,2}}{\lambda_i - \mathbf{C}[k,l]^{1,1}} \\ 1 \end{bmatrix}, \; \mathbf{u}_i = \frac{\mathbf{u}'_i}{||\mathbf{u}'_i||}, \; i \in \{1, 2\} \quad (9)$$

where $||\mathbf{u}'_i||$ is the Euclidean norm. For the particular case of the matrix (7), we have

$$\begin{aligned} t &= (\delta_1 + \delta_2)(|h_1|^2 + |h_2|^2) \quad (10) \\ d &= (\delta_1 - \delta_2)^2|h_1|^2|h_2|^2 - (\delta_1|h_1|^2 + \delta_2|h_2|^2)(\delta_1|h_2|^2 + \delta_2|h_1|^2) \\ &= -\delta_1\delta_2(|h_1|^2 + |h_2|^2)^2 \quad (11) \end{aligned}$$

Substituting in (8), the eigenvalue spread of matrix $\mathbf{C}[k,l]$ is given by

$$\begin{aligned} L &= |\lambda_1 - \lambda_2| = |\sqrt{t^2 + 4d}| \\ &= |\sqrt{(\delta_1 + \delta_2)^2(|h_1|^2 + |h_2|^2)^2 - 4\delta_1\delta_2(|h_1|^2 + |h_2|^2)^2}| \\ &= |\sqrt{(\delta_1 - \delta_2)^2(|h_1|^2 + |h_2|^2)^2}| \\ &= |\delta_1 - \delta_2|(|h_1|^2 + |h_2|^2) \end{aligned} \quad (12)$$

Recall that the cumulant matrix $\mathbf{C}[1,1]$ corresponds to $\delta_1 = |h_1|^2$ and $\delta_2 = |h_2|^2$, so, its eigenvalue spread is

$$L_1 = |(|h_1|^2 - |h_2|^2)(|h_1|^2 + |h_2|^2)| = ||h_1|^4 - |h_2|^4| \quad (13)$$

In the case of $\mathbf{C}[1,2]$, we have $\delta_1 = -\delta_2 = h_1h_2$ and the eigenvalue spread is

$$L_2 = |(h_1h_2 + h_1h_2)(|h_1|^2 + |h_2|^2)| = 2|h_1||h_2|(|h_1|^2 + |h_2|^2) \quad (14)$$

2.3. Proposed approach

In order to estimate the channel matrix, we propose to compute the eigenvectors of the 4th-order cumulant matrix with highest eigenvalue spread. The matrix, $\mathbf{C}[1,1]$ or $\mathbf{C}[1,2]$, is selected according to the following decision criterion

$$\frac{L_2}{L_1} = \frac{2|h_1||h_2|(|h_1|^2 + |h_2|^2)}{||h_1|^2 - |h_2|^2|(|h_1|^2 + |h_2|^2)} = \frac{2|h_1||h_2|}{||h_1|^2 - |h_2|^2|} \underset{\mathbf{C}[1,2]}{\overset{\mathbf{C}[1,1]}{\lessgtr}} 1$$

From equations (16) and (18), showed in the appendix, we conclude that this criterion can be implemented in the practice from 4th-order cumulants,

$$\begin{aligned} \frac{L_2}{L_1} &= \frac{|c_4(x_2, x_2^*, x_1, x_1^*)|}{|c_4(x_1, x_2^*, x_1, x_1^*)|} = \frac{2|h_1|^2|h_2|^2}{||h_1|^2 - |h_2|^2||h_1||h_2|} \\ &= \frac{2|h_1||h_2|}{||h_1|^2 - |h_2|^2|} \underset{\mathbf{C}[1,2]}{\overset{\mathbf{C}[1,1]}{\lessgtr}} 1 \end{aligned} \quad (15)$$

Summarising, the method for Blind Channel Estimation based on Eigenvalue Spread (BCEES) consists in performing the following four steps:

1. Compute $\mathbf{C}[1,1]^{2,2} = c_4(x_2, x_2^*, x_1, x_1^*)$ and $\mathbf{C}[1,1]^{1,2} = c_4(x_1, x_2^*, x_1, x_1^*)$ from K samples of the observed signals x_1 and x_2.
2. **If** $\frac{|\mathbf{C}[1,1]^{2,2}|}{|\mathbf{C}[1,1]^{1,2}|} < 1$, then compute the cumulant into $\mathbf{C}[1,1]$ using (16) from K samples of the observed signals:

$$\mathbf{C}[1,1]^{1,1} \quad = \quad c_4(x_1, x_1^*, x_1, x_1^*)$$

Note that the 4th-order cumulant $\mathbf{C}[1,1]^{2,1} = (\mathbf{C}[1,1]^{1,2})^*$ has been computed in step 1.

Else, compute the cumulants into $\mathbf{C}[1,2]$ using (18) from K samples of the observed signals:

$$\begin{aligned} \mathbf{C}[1,2]^{1,2} &= c_4(x_1, x_2^*, x_1, x_2^*), \\ \mathbf{C}[1,2]^{2,2} &= c_4(x_2, x_2^*, x_1, x_2^*) \end{aligned}$$

Note that the 4th-order cumulants $\mathbf{C}[1,2]^{1,1} = \mathbf{C}[1,1]^{1,2}$ and $\mathbf{C}[1,2]^{2,1} = \mathbf{C}[1,1]^{2,2}$ have been computed in step 1.
3. Compute the eigenvalues using (8) and the eigenvectors using (9).
4. The channel matrix is estimated by $\hat{\mathbf{H}} = [\mathbf{u}_1 \ \mathbf{u}_2]$ and the signals are recovered using $\hat{\mathbf{s}} = \hat{\mathbf{H}}^H \mathbf{x}$.

3. SIMULATION RESULTS

This section presents the result of several simulations carried out to compare the performance of several eigen-based algorithms:

- The method proposed in [10] which computes the eigendecomposition of matrix $\mathbf{C}[1,1]$. We will show that for some channel distributions, the performance is improved by considering the matrix $\mathbf{C}[1,2]$.
- The method proposed in [11] which computes the eigendecomposition of a linear combination of 4th-order cumulant matrices: $\mathbf{C}[1,1] - \mathbf{C}[2,2]$
- The novel method BCEES proposed in Subsection 2.3.
- The JADE algorithm proposed in [8] based on diagonalising simultaneously several 4th-order cumulant matrices. Since the channel matrix is orthogonal, the whitening step has been not considered in the code.

The experiments have been performed by simulating the transmission of QPSK signals coded with the Alamouti coding scheme over Rayleigh-distributed channels. We assume that the channel remains constant during the transmission of a block of $K = 500$ symbols. The cumulants are calculated for each block by sample averaging over the symbols. The performance has been measured in terms of the Symbol Error Rate (SER) obtained by averaging the results for 1,000,000 independent realizations.

First, we will show the importance of selecting the 4th-order cumulant matrix with highest eigenvalue spread. Figure 2 plots the SER obtained by diagonalising only one matrix ($\mathbf{C}[1,1]$ and $\mathbf{C}[1,2]$) versus its eigenvalue spread for a SNR of 10 dB. Note that both methods provide a high SER for small values of the eigenvalue spread. It is also apparent that better results are obtained by diagonalising only $\mathbf{C}[1,2]$.

Figure 3 shows the SER versus de SNR obtained with the eigen-based approaches above described. For comparison purposes we also present the SER obtained with Perfect Channel Side Information (Perfect CSI). It can be seen that the worst performance is obtained when the channel is estimated using only the 4th-order cumulant matrix $\mathbf{C}[1,1]$ or a linear combination of two matrices, $\mathbf{C}[1,1]-\mathbf{C}[2,2]$. Observe that the performance of this methods is improved by considering $\mathbf{C}[1,2]$ but, however, this approach presents a bad performance of high SNRs. Note also that BCEES and JADE achieve the optimum performance.

Approach	Time (seconds)
Beres-Adve: $\mathbf{C}[1,1]$	3.5061
$\mathbf{C}[1,2]$	4.2775
$\mathbf{C}[1,1] - \mathbf{C}[2,2]$	4.6519
BCEES	4.5457
JADE	6.4483

Table 1. Time needed to process 10^4 packets of $K = 500$ symbols

Finally, Table 1 shows the time needed to process 10^4 packets by `Matlab` code running in a core of a `PC` with an `Intel Core 2 Quad Q6600 2.4 GHz` processor and 2 GB of RAM. It is apparent the considerable difference between JADE and BCEES.

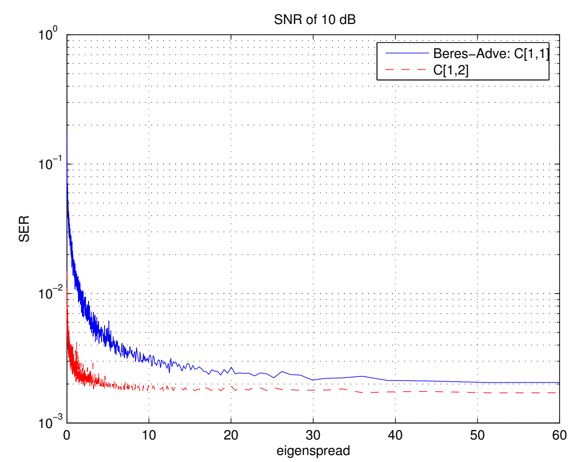

Fig. 2. SER versus eigenvalue spread

4. CONCLUSION

This paper presents a novel blind channel estimation algorithm for systems with the 2×1 Alamouti space-time block coding. We show that the 2×2 matrices containing 4th-order cumulants of the observed signals can be decomposed in two matrices: the channel matrix (eigenvectors) and a diagonal matrix (eigenvalues) whose inputs depend on the channel realization. As a consequence, the channel matrix can be obtained by performing an eigendecompostion of the cumulant matrices. In order to estimate the channel, we have proposed to diagonalise the 4th-order cumulant matrix with maximum eigenvalue spread. Simulation results show that the novel approach presents the same performance than JADE with lower computational load.

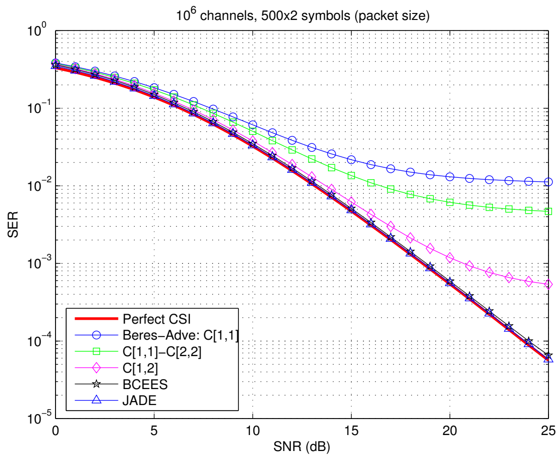

Fig. 3. SER obtained for a transmission of QPSK symbols over Rayleigh channels

Appendix

For the 2×1 Alamouti coding scheme, there are four different 4th-order cumulant matrices given by

$$\mathbf{C}[1,1] = \begin{bmatrix} c_4(x_1, x_1^*, x_1, x_1^*) & c_4(x_1, x_2^*, x_1, x_1^*) \\ c_4(x_2, x_1^*, x_1, x_1^*) & c_4(x_2, x_2^*, x_1, x_1^*) \end{bmatrix} \quad (16)$$
$$= \rho_4 \cdot \begin{bmatrix} |h_1|^4 + |h_2|^4 & (|h_1|^2 - |h_2|^2) h_1 h_2 \\ (|h_1|^2 - |h_2|^2)(h_1 h_2)^* & 2|h_1|^2 |h_2|^2 \end{bmatrix}$$

$$\mathbf{C}[2,2] = \begin{bmatrix} c_4(x_1, x_1^*, x_2, x_2^*) & c_4(x_1, x_2^*, x_2, x_2^*) \\ c_4(x_2, x_1^*, x_2, x_2^*) & c_4(x_2, x_2^*, x_2, x_2^*) \end{bmatrix} \quad (17)$$
$$= \rho_4 \cdot \begin{bmatrix} 2|h_1|^2 |h_2|^2 & (|h_2|^2 - |h_1|^2) h_1 h_2 \\ (|h_2|^2 - |h_1|^2)(h_1 h_2)^* & |h_1|^4 + |h_2|^4 \end{bmatrix}$$

$$\mathbf{C}[1,2] = \begin{bmatrix} c_4(x_1, x_1^*, x_1, x_2^*) & c_4(x_1, x_2^*, x_1, x_2^*) \\ c_4(x_2, x_1^*, x_1, x_2^*) & c_4(x_2, x_2^*, x_1, x_2^*) \end{bmatrix} \quad (18)$$
$$= \rho_4 \cdot \begin{bmatrix} (|h_1|^2 - |h_2|^2) h_1 h_2 & 2 h_1^2 h_2^2 \\ 2|h_1|^2 |h_2|^2 & (|h_2|^2 - |h_1|^2) h_1 h_2 \end{bmatrix}$$

and $\mathbf{C}[2,1] = \mathbf{C}[1,2]^H$. In this appendix we show that these matrices can be written as

$$\mathbf{C}[k,l] = c_4(\mathbf{x}, \mathbf{x}^H, x_k, x_l^*) = \rho_4 \cdot \mathbf{H} \cdot \mathbf{\Delta}[k,l] \cdot \mathbf{H}^H \quad (19)$$

From the signal model in equation (2), we obtain

$$\begin{aligned} \mathbf{C}[k,l] &= c_4(\mathbf{x}, \mathbf{x}^H, x_k, x_l^*) = c_4(\mathbf{H}\mathbf{s}, \mathbf{s}^H \mathbf{H}^H, x_k, x_l^*) \\ &= \mathbf{H} \cdot c_4(\mathbf{s}, \mathbf{s}^H, x_k, x_l^*) \cdot \mathbf{H}^H \quad (20) \end{aligned}$$

where

$$c_4(\mathbf{s}, \mathbf{s}^H, x_k, x_l^*) = \begin{bmatrix} c_4(s_1, s_1^*, x_k, x_l^*) & c_4(s_1, s_2^*, x_k, x_l^*) \\ c_4(s_2, s_1^*, x_k, x_l^*) & c_4(s_2, s_2^*, x_k, x_l^*) \end{bmatrix} \quad (21)$$

Using the properties of the cumulants, we obtain that the non-zero cumulants are

$$\begin{aligned} &c_4(s_1, s_1^*, x_k, x_l^*) \\ &\quad = c_4(s_1, s_1^*, \mathbf{H}^{k,1} s_1 + \mathbf{H}^{k,2} s_2, (\mathbf{H}^{k,1})^* s_1^* + (\mathbf{H}^{l,2})^* s_2^*) \\ &\quad = \mathbf{H}^{k,1} (\mathbf{H}^{l,1})^* c_4(s_1, s_1^*, s_1, s_1^*) = \mathbf{H}^{k,1} (\mathbf{H}^{l,1})^* \rho_4 \quad (22) \end{aligned}$$

$$\begin{aligned} &c_4(s_2, s_2^*, x_k, x_l^*) \\ &\quad = c_4(s_2, s_2^*, \mathbf{H}^{k,1} s_1 + \mathbf{H}^{k,2} s_2, (\mathbf{H}^{k,1})^* s_1^* + (\mathbf{H}^{l,2})^* s_2^*) \\ &\quad = \mathbf{H}^{k,2} (\mathbf{H}^{l,2})^* \rho_4 \quad (23) \end{aligned}$$

where $\mathbf{H}^{k,l}$ represents the elements in the k-th row, l-th column of $\mathbf{H}$. As a consequence,

$$\begin{aligned} c_4(\mathbf{s}, \mathbf{s}^H, x_k, x_l^*) &= \rho_4 \cdot \begin{bmatrix} \mathbf{H}^{k,1} (\mathbf{H}^{l,1})^* & 0 \\ 0 & \mathbf{H}^{k,2} (\mathbf{H}^{l,2})^* \end{bmatrix} \\ &= \rho_4 \cdot \mathbf{\Delta}[k,l] \quad (24) \end{aligned}$$

5. REFERENCES

[1] D. Gesbert, M. Shafi, D. Shan-Shiu, P. J. Smith, and A. Naguib, "From theory to practice: an overview of mimo space-time coded wireless systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 3, pp. 281–302, 2003.

[2] A. J. Paulraj and C. B. Papadias, "Space-time processing for wireless communications," *IEEE Signal Processing Magazine*, vol. 14, no. 6, pp. 49–83, November 1997.

[3] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1451–1458, October 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, July 1999.

[5] C. Budianu and L. Tong, "Channel estimation for space-time orthogonal block codes," in *Proceedings of International Conference on communications*, June 2001, pp. 1127–1131.

[6] A. F. Naguib, V. Tarokh, N. Seshadri, and A. R. Calderbank, "A space-time coding modem for high-data-rate wireless," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1459–1478, October 1998.

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

[8] J.-F Cardoso and A. Souloumiac, "Blind beamforming for non-gaussian signals," *IEE Proceedings F*, vol. 140, no. 46, pp. 362–370, 1993.

[9] C. Nikias and J. Mendel, "Signal processing with higher-order spectra," *IEEE Signal Processing Magazine*, pp. 10–35, July 1993.

[10] E. Beres and R. Adve, "Blind channel estimation for orthogonal stbc in miso systems," in *Proceedings of Global Telecommunications Conference*, November 2004, vol. 4, pp. 2323–2328.

[11] H. J. Pérez-Iglesias, A. Dapena, L. Castedo, and V. Zarzoso, "Blind channel identification for alamouti's coding systems based on eigenvector decomposition," in *Proceedings of European Wireless 2007*, Paris, France, April 2007.