

## Detection scheme for linear dispersion space-time block codes using modified SQRD decomposition

### Esquema de detección para códigos espacio-temporales de bloque, basados en códigos de dispersión lineal utilizando la descomposición Sorted QR

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**Palabras clave:** sistemas mimo; códigos espacio-temporales de dispersión lineal; descomposición QR

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#### Resumen

En el presente trabajo se presenta una nueva arquitectura para detección de sistemas híbridos MIMO en canales con desvanecimiento Rayleigh. El esquema propuesta consiste de un módulo Alamouti más  $n_s$  antenas operando con diversidad espacial en el transmisor. El receptor propuesto está basado en el algoritmo *Sorted QR decomposition* (SQRD) presentado en (Wubben *et al.*, 2001). Nuestra propuesta disminuye significativamente la complejidad manteniendo las ventajas del esquema SQRD, obteniéndose una considerable ganancia en términos de Tasa de Error de Bit (BER), sacrificando una disminución en la tasa de trasmisión.

#### Abstract

In this work, a novel architecture for detection of Hybrid MIMO Systems over Rayleigh fading channels is presented. The Hybrid MIMO scheme consists of one Alamouti space-time block code unit, plus  $n_s$  antennas operating as layers of V-BLAST in the transmitter. The proposed receiver is based on the algorithm *Sorted QR decomposition* (SQRD) presented in (Wubben *et al.*, 2001). This proposal reduces significantly the complexity while maintaining the advantages of the SQRD scheme, obtaining a considerable gain in performance in terms of bit error rate (BER) at the expense of decreasing data rate.

**Keywords:** Hybrid MIMO systems; linear dispersion space-time codes; QR decomposition.

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## Introduction

The demand for communication systems that effectively exploit the wireless channel's limited capacity (Telatar, 1999) has rapidly grown during the last decade. In recent years, multiple-input, multiple-output (MIMO) systems have emerged as an attractive technique to increase the bit rate without increasing neither power nor bandwidth resources. A MIMO system employs multiple antennas, both at the transmitter and the receiver, adding an extra degree of freedom in the design of communication systems. In particular, two techniques have been developed to take advantage of MIMO systems: *Spatial Multiplexing and Diversity Transmission*. The first technique aims at increasing the spectral efficiency. One of its main proponents is *Sorted QR decomposition* (SQRD), which was first introduced in (Wubben *et al.*, 2001). The second technique is aimed at increasing diversity gain. This was achieved by the Space-Time Block Codes (STBC) (Tarokh *et al.*, 1999). The implementation of STBC decoders is relatively easy to carry out, but one drawback is that their spectral efficiency is low. A popular scheme that reaches full diversity and full-rate was proposed by Alamouti in (Alamouti, 1998).

SQRD can attain very high spectral efficiency while maintaining a very low complexity of their receiver. However, because it does not obtain the optimal detection order, and use a scheme of Successive Cancellation Interference (SIC), it suffers great degradation due to the error propagation, in his decision feedback. In (Raza *et al.*, 2004) a scheme called KIL-VBLAST was proposed, whose main goal is diminishing the error propagation between layers, it sacrifices spectral efficiency because it transmits a known symbol in the receiver. In this case, they propose that it belongs at the first sub-stream to detect, with this proposal the total diversity of V-BLAST is increased achieved a better performance, their principal disadvantage is that need hardware resources to transmit known information. In (Jiang *et al.*, 2005), a scheme called GMD-VBLAST was proposed, these scheme uses a joint transceiver in the receiver and the transmitter based on the Geometric Mean Decomposition (GMD) .

It achieves a better performance than V-BLAST, maintaining their high spectral efficiency. However, the complexity of the receiver and transmitter is increased considerably, and it also needs Channel State Information (CSI) to work, therefore their hardware implementation can be complicated and expensive.

An alternative approach, known as *hybrid coding* (HC) (Mao, Motani, 2005), (Meng, Tuqan, 2007), (Cortez, *et al.*, 2007), (Longoria, *et al.*, 2007), (Bazdresch, *et al.*, 2012) consists in

the selection of some of the available transmitting antennas to work in STBC mode, while the remaining ones operate as V-BLAST. In particular, the STBC-VBLAST scheme (Mao, Motani, 2005), (Meng, Tuqan, 2007) is an interesting example of hybrid coding, as it uses  $n_B$  Alamouti layers and  $n_s$  spatial layers, increasing spectral efficiency over pure STBC, and its structure allows using an OSIC scheme decoding based on the  $QR$  decomposition. The principal disadvantage of (Meng, Tuqan, 2007) is that it has high receiver complexity and for (Mao, Motani, 2005) is that it needs two kinds of decoders in the receiver: STBC decoder and V-BLAST decoder. Also, the spectral efficiency of the system is greatly diminished when the number of Alamouti encoders is increased in the transmitter.

This paper presents a modification to the hybrid coding system proposed in (Mao, Motani, 2005). The scheme consists of only one Alamouti space-time block code unit in the last layer, plus  $n_s$  antennas operating as V-BLAST in the transmitter. We obtained an equivalent channel matrix using the Linear Dispersion Space-Time Codes (LDCs) techniques proposed in (Hassibi, Hochwald, 2002), with this rearrangement we can achieve the benefits of the schemes described previously (Wubben, *et al.*, 2001), (Raza, *et al.*, 2004).

The receiver is based on scheme proposed in (Wubben, *et al.*, 2001). It refers to this new architecture as ZF-SQRD-LDSTBC, the estimation and detection of the transmitted symbols are carried out of identical way as in SQRD (Wubben, *et al.*, 2001). The Symbols exhibiting diversity gain (Alamouti Layer) are detected first, followed by the ordered spatially-multiplexed symbols.

The scheme proposal increased the total diversity of the system and mainly of the first layer to detect, and since the receiver is based on the scheme proposed in (Wubben, *et al.*, 2001), in this case, an efficient detector with low complexity was proposed, a better performance is obtained, and no CSI is needed in this case. Therefore, an implementation can be carried out in hardware at lower costs. The implementation of the *sorted QR decomposition* was done using *Modified Gram-Schmidt algorithm* (MGS) (Golub, Van Loan, 1996). The scheme exploit the special matrix structure that comes from the LDCs representation to improve the lower complexity of the receiver proposed in (Wubben, *et al.*, 2001).

This proposal was compared with the schemes proposed in (Wubben, *et al.*, 2001), (Raza, *et al.*, 2004). The results obtained shown that, at the same spectral efficiency, this proposal outperforms both schemes in terms of achieved Bit Error Rate (BER), with the same number of

receiver and transmitter antennas. With respect to the scheme proposed in (Jiang, *et al.*, 2005), this scheme achieves a lower performance but with a less computational complexity. In the next sections, the system model, method and results were presented.

## Method

A space-time block code (STBC) is a mapping from a vector of symbols to a space-time code matrix that specifies how symbols are transmitted over the available antennas and time intervals. The STBC-VBLAST linear space-time block code transmits  $2n_s + 1$  complex symbols over  $T = 2$  symbol intervals and  $n_T$  transmit antennas. We assume the receiver uses  $n_R$  antennas. A full description was shown in this section of the paper.

### a. Linear dispersion codes (LDC)

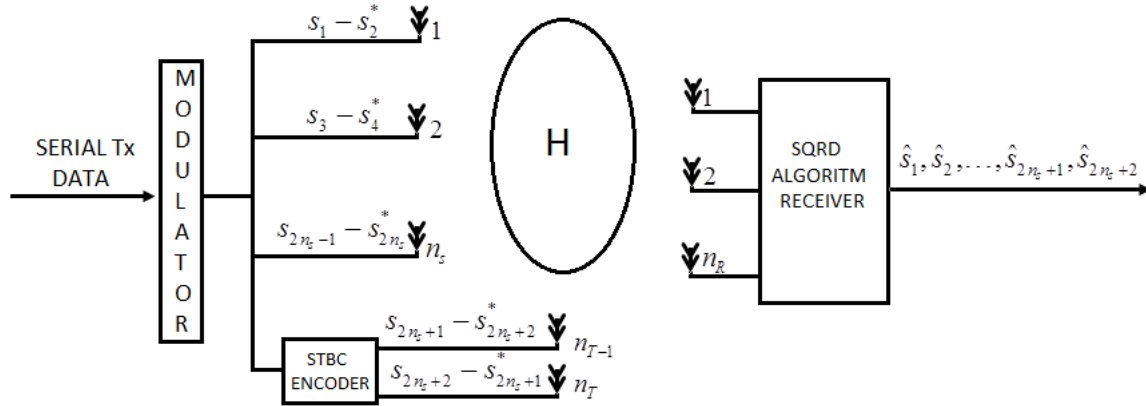
An LDC codeword is defined as a matrix  $S$  given by:

$$S = \sum_{q=1}^Q (\alpha_q A_q + \beta_q B_q) \quad (1)$$

Where we have assumed that  $Q$  symbols are transmitted in a codeword, each symbol  $S_q = \alpha_q + j\beta_q$ , and the complex linear dispersion matrices  $A_q$  and  $B_q$  (of size  $m \times n_T$ ) specify the code. The columns of  $A_q$  and  $B_q$  represent the antenna for which the symbol  $S_q$  is through at the channel and the rows indicates the time instant when this event happened.

### b. Channel model

The propagation channel between each transmitting and receiving antenna can be modeled as a Rayleigh narrowband stationary stochastic process. Also this work considers that the channel is scatterer-rich at both the transmitter and receiver ends.



**Fig.1.** ZF-SQRD-LDSTBC Transmitter/Receiver

The MIMO channel can be modeled as a random matrix  $H$  of size  $n_R \times n_T$ , where  $n_R$  and  $n_T$  represent the number of antennas at the receiver and transmitter, respectively. The elements of  $H$  are denoted  $h_{ij}$ , for  $i = 1, 2, \dots, n_R$ ,  $j = 1, 2, \dots, n_T$ . Each element of  $H$  is a sample of a complex Gaussian random variable with zero mean and variance 0.5 per dimension. We assume that the channel fading is slow, and the channel matrix  $H$  remains constant during the transmission of one space-time codeword of duration  $m_T$ . A new realization of the channel matrix, independent of the previous one, is then generated for each new space-time codeword. We assume that all the antennas transmit information symbols from the same  $M$ -QAM constellation map, and that the receiver has a CSI perfectly synchronized. The total transmitted power is normalized to 1 watt.

### a. ZF-SQRD-LDSTBC Transmitter

ZF-SQRD-LDSTBC employs  $n_T = n_S + n_A$  elements to transmit and  $n_R$  elements to receive, with  $n_L$  spatial multiplexing layers, where  $n_S$  is the number of antennas operating as V-BLAST in the transmitter. In the first  $n_L - 1$  layers one spatially multiplexed antenna is used, while in the  $n_L$  layer an Alamouti STBC encoder with  $n_A = 2$  transmitting antennas and with a block length  $m = 2$  is used. It has a spectral efficiency of  $n_T - 1$  symbols per channel use. The scheme needed  $n_R > n_T - 1$  antennas to operate in the receiver. A simplified block diagram of the ZF-SQRD-

LDSTBC system based on the scheme proposed in (Bazdresch, *et al.*, 2012) is shown in the Figure 1.

The received signal is represented by the  $n_R \times 2$  matrix:

$$Y = HS + N \quad (2)$$

Where  $N$  is a matrix of complex Gaussian random noise variables with zero mean and independent real and imaginary parts with variance  $\sigma_n^2 = N_0/2$  per dimension. In Table I, the proposed coding scheme is done in space and time over the antenna arrangement for the symbol sequence  $s_1, s_2, \dots, s_{nsym}$ , where  $nsym = n_A n_S + 2$  and  $n_A = 2$ .

**Table 1.** Antenna Mapping for ZF-SQRD-LDSTBC Scheme.

	<b>Spatial Antennas</b>	<b>Alamouti STBC-Block</b>	
Time	Antenna $V = 1, 2, \dots, n_S$	Antenna 1	Antenna 2
$t$	$S_V$	$S_{n_A n_{s+1}}$	$S_{n_A n_{s+2}}$
$t + T$	$-S_{V+1}^*$	$-S_{n_A n_{s+2}}^*$	$-S_{n_A n_{s+1}}^*$

## ZF-SQRD-LDSTBC Receiver

Under the assumption that the Channel State Information (CSI) is perfectly known by the receiver and in presence of Gaussian noise, the detection and decoding process of the transmitted signal vector  $S$ , at the  $m^{th}$  time block slice, where  $t = 1; 2$  and the minimum number of two antennas per STBC,  $n_A = 2$ , the receive signal in equation 2 can be expressed as:

$$\begin{bmatrix} y_1^{(1)} & y_1^{(2)} \\ y_2^{(1)} & y_2^{(2)} \\ \square & \square \\ \square & \square \\ \square & \square \\ y_{nR}^{(1)} & y_{nR}^{(2)} \end{bmatrix} = \begin{bmatrix} h_{1,1} & \dots & y_1^{(2)} \\ h_{2,1} & \dots & y_2^{(2)} \\ \vdots & \ddots & \vdots \\ h_{nR,1} & \dots & h_{nR,nT} \end{bmatrix} = \begin{bmatrix} S_{spa} \\ S_A \end{bmatrix} + \begin{bmatrix} n_1^{(1)} & n_1^{(2)} \\ n_2^{(1)} & n_2^{(2)} \\ \vdots & \vdots \\ n_{nR}^{(1)} & n_{nR}^{(2)} \end{bmatrix} \quad (3)$$

In Equation 3, and from now on, the subscript indicate the correspondent transmitter or receiver antenna, and the super-indices indicate the correspondent block emission time  $t$ . Where  $S$  is defined as:

$$\begin{bmatrix} S_{spa} \\ S_A \end{bmatrix} \quad (4)$$

And its respective blocks have the structure indicated as follows:

$$S_{spa} = \begin{bmatrix} S_1 & S_2^* \\ S_3 & S_4^* \\ \vdots & \vdots \\ S_{2nS-1} & S_{2nS}^* \end{bmatrix} = \begin{bmatrix} S_1^{(1)} & S_2^{(2)} \\ S_2^{(1)} & S_2^{(2)} \\ \vdots & \vdots \\ S_{nS}^{(1)} & S_{nS}^{(2)} \end{bmatrix} \quad (5)$$

And

$$S_A = \begin{bmatrix} S_1^{(1)A} & S_1^{(2)A} \end{bmatrix} = \begin{bmatrix} S_{nAn_s+1} - S_{nAn_s+2}^* \\ S_{nAn_s+2} - S_{nAn_s+1}^* \end{bmatrix} \quad (6)$$

In Equations 5 and 6, the matrix at the left indicates the symbol arrangement in the antennas and the notation introduced in the right matrix has been elaborated to simplify the explanation of the detection algorithm. Note that the matrix  $S_{spa}$  corresponds to the symbols transmitted by V-BLAST layers and  $S_A$  to Alamouti-STBC encoder.

The system Equation 3 can be reformulated as a LDSTBC code according to (Hassibi, Hochwald, 2002). The resultant expression is

$$\begin{bmatrix} y_1^{(1)} \\ y_1^{(2)*} \\ \vdots \\ y_{n_R}^{(1)} \\ y_{n_R}^{(2)*} \end{bmatrix} = \begin{bmatrix} H_{spa} & H_A \end{bmatrix} S_{LD} + \begin{bmatrix} n_1^{(2)} \\ n_1^{(2)*} \\ \vdots \\ n_{n_R}^{(1)} \\ n_{n_R}^{(2)*} \end{bmatrix} \quad (7)$$

The Equation 7 can be reformulated in compact form as:

$$Y_{LD} = H_{LD} S_{LD} + N_{LD} \quad (8)$$

Where  $H_{LD}$  is named *Linear Dispersion Matrix*, and its sub matrices are defined by:

$$H_{spa} = \begin{bmatrix} H_{1,1}^{spa} & H_{1,2}^{spa} & \cdots & H_{1,n_S}^{spa} \\ H_{2,1}^{spa} & H_{2,2}^{spa} & \cdots & H_{2,n_S}^{spa} \\ \vdots & \vdots & \ddots & \vdots \\ H_{n_R,1}^{spa} & H_{n_R,2}^{spa} & \cdots & H_{n_R,n_S}^{spa} \end{bmatrix} \quad (9)$$

Where

$$H_{ij}^{spa} = \begin{bmatrix} h_{i,j} & 0 \\ 0 & -h_{i,j}^* \end{bmatrix} \quad (10)$$

For  $i = 1, 2, \dots, n_R$  and  $j = 1, 2, \dots, n_S$ .

$$H_A = \begin{bmatrix} H_{11}^A \\ H_{21}^A \\ \vdots \\ H_{n_R 1}^A \end{bmatrix} \quad (11)$$

Where each element of equation 11 is given by:



$$H_{k1}^A = \begin{bmatrix} h_{k,n_A n_S+1} & h_{k,n_A n_S+2} \\ h_{k,n_A n_S+2}^* & -h_{k,n_A n_S+1}^* \end{bmatrix} \quad (12)$$

For  $k = 1, 2, \dots, n_R$ . The matrix  $H_{ij}^{spa}$  is the portion of  $H_{LD}$  that links the  $j^{th}$  spatial antenna with the  $i^{th}$  receiver antenna. The same applies to  $H_{k1}^A$  that links the Alamouti block to the  $k^{th}$  receiver antenna.

A matrix structure similar to Equation 11 is shown in (Longoria, *et al.*, 2007). The reformulation of equation 8 of the system equation 3, lead to the next rearrangement of matrix  $S$

$$S_{LD} = \begin{bmatrix} S_{LD}^{spa} \\ S_{LD}^A \end{bmatrix} \quad (13)$$

Where

$$S_{LD}^{spa} = \begin{bmatrix} s_1^{(1)} \\ s_1^{(2)} \\ \vdots \\ s_{n_S}^{(1)} \\ s_{n_S}^{(2)} \end{bmatrix} \quad (14)$$

And

$$S_{LD}^A = \begin{bmatrix} s_1^{(1)A} \\ s_2^{(1)A} \end{bmatrix} \quad (15)$$

The reformulation of Equation 3 as Equation 8 allows to consider the MIMO system as an equivalent version with  $n_{sym}$  transmit antennas, ignoring any distinction between STBC block and V-BLAST layers.

In this way, we propose a modified and optimized SQRD that can be applied directly over  $H_{LD}$  to use a simple linear detection (OSIC), using the output permutation vector order during

the reordering stage, like is presented in (Wubben, *et al.*, 2001). The distribution of power between antennas was done using the next equations:

$$P_s = 2/(2n_T - 2); P_A = P_s/2 \quad (16)$$

Where  $P_s$  and  $P_A$  correspondent to the power feed at the antennas spatial (V-BLAST) and the antennas used in the layer of Alamouti respectively. The objective with this distribution is to send all the symbols with the same power.

### **b. ZF-SQRD-LDSTBC as Linear dispersion space-time code**

The transmission matrix  $S_{LD}$  for ZF-SQRD-LDSTBC can be specified for the next expression

$$S_{LD} = \sum_{i=1}^{nsym} \{\alpha_i + j\beta_i\} = A + jB \quad (17)$$

The dispersion matrices  $A$  and  $B$  for  $m=2$  and  $nsym = n_A n_s + 2$  for  $S_{LD}$  are:

$$A = [A_i] B = [B_i] \quad (18)$$

For  $i = 1, 2, \dots, n_s + 1$ .

Where  $A_i$  and  $B_i$  was defined for the spatial layers  $i \leq n_s$  as:

$$A_i = \begin{bmatrix} \alpha_i & 0 \\ 0 & -\alpha_{i+1} \end{bmatrix}, \quad B_i = \begin{bmatrix} \beta_i & 0 \\ 0 & \beta_{i+1} \end{bmatrix} \quad (19)$$

And for the Alamouti layer  $i = n_s + 1$  was defined as:

$$A_i = \begin{bmatrix} \alpha_i & \alpha_{i+1} \\ \alpha_{i+1} & -\alpha_i \end{bmatrix}, \quad B_i = \begin{bmatrix} \beta_i & \beta_{i+1} \\ -\beta_{i+1} & \beta_i \end{bmatrix} \quad (20)$$

### c. Modified SQRD

For the detection of the  $nsym$  transmitted symbols, is necessary to calculate the  $QR$  decomposition of  $H_{LD} = Q_{LD}R_{LD}$ , apparently if the MGS algorithm was applied directly, the complexity is increased meaningfully, because the dimensions of  $H_{LD}$ .

By taking advantage of the structure of  $H_{LD}$  is possible to split the  $QR$  decomposition in two parts, first the part correspondent to the spatial layers was obtained and after the part of the Alamouti layer was obtained. It is important to mention that we work with the original matrix  $H$  and obtain  $H = Q_m R_m$ , from which is possible to obtain  $H_{LD}$  applying the equivalences defined in (Longoria, et. al., 2007), (Bazdresch, et. al., 20102) therefore is possible to have a complexity similar at the algorithm showed in (Wubben, et al., 2001). The complete algorithm is shown in the Algorithm 1. The ordered of detection only is applied in the part of the scheme correspondent at V-BLAST layers. Also a modification to calculate the *norms* (we called  $norm(x)_{est}$ ) of the columns of  $H$  used in the order which the symbols were established. With this modification, an important quantity of *flops* was saved.

#### G. $norm(x)_{est}$ calculate

In order to decrease the complexity of the QR decomposition and because the elements of  $H$  have a distribution Gaussian, we can use an estimator in the calculation of the energy of  $H$  to obtain the *detection order*, such as was described in (Kim, et al., 2006). We have found that the performance is the same using the estimator or the exact equation, therefore a meaningful saving of *flops* is achieved. The equation to calculate the exact energy of a column vector  $x$  is

$$\|x\|^2 = x^H x \quad (21)$$

The estimator that we used to calculate the energy of a column vector  $x$  is

$$norm(x)_{est} = sum\{|R_e(x(:, :))|\} + sum\{|I_m(x(:, :))|\} \quad (22)$$

**Algorithm 1 Modified SQRD**

- 
- 1: First we calculate the *QR* decomposition of *spatial layers*
  - 2: Input:  $H^{n_R \times n_T}$ ,  $R_m^{n_T \times n_T} = 0$ ,  $order = 1:1:n_A n_S + 2$ .
  - 3: Let  $Q_m = H$ .
  - 4: **for**  $k = 1$  to  $n_S$  **do**
  - 5:  $ind = argmin_{j=k:n_S} norm(Q_m(:,j))_{est}$
  - 6: exchange columns  $k$  and  $ind$  for  $Q_m$ ,  $R_m$ .
  - 7: exchange columns  $2k$  and  $2k - 1$  for columns  $2ind$  and  $2ind - 1$  for  $order$ .
  - 8:  $R_m(k,k) = \|Q_m(:,k)\|_2$
  - 9:  $Q_m(:,k) = Q_m(:,k)/R_m(k,k)$
  - 10: **for**  $j = k + 1$  to  $n_T$  **do**
  - 11:  $R_m(k,j) = Q_m(:,k) * Q_m(:,j)$
  - 12:  $Q_m(:,j) = Q_m(:,j) - Q_m(:,k) R_m(k,j)$
  - 13: **endfor**
  - 14: **endfor**
  - 15: Next we calculate the *QR* decomposition of *Alamouti layer*
  - 16: First we built the columns  $nsym - 1$  without normalize of  $Q_{LD}$  using  $Q_m$  based in the equivalences of (Longoria, *et al.*, 2007)
  - 17:  $Q_{LD}(1:2:2n_R - 1, nsym - 1) = Q_m(:, n_S - 1)$ .
  - 18:  $Q_{LD}(2:2:2n_R, nsym - 1) = Q_m(:, n_S)^*$ .
  - 19: Next we normalize  $Q_{LD}(:, nsym - 1)$ .
  - 20:  $R_m(nsym - 1, nsym - 1) = \|(:, nsym - 1)\|_2$
  - 21:  $Q_m(:, n_S - 1) = Q_{LD}(:, nsym - 1) / R_m(nsym - 1, nsym - 1)$
  - 22: We obtain the last column and row for  $Q_{LD}$  and  $R_m$  respectively using (Longoria, *et al.*, 2007)
  - 23:  $Q_{LD}(1:2:2n_R - 1, nsym) - Q_{LD}(2:2:2n_R, nsym - 1)^*$
  - 24:  $Q_{LD}(2:2:2n_R, nsym) = Q_{LD}(1:2:2n_R - 1, nsym)^*$
  - 25:  $R_m(nsym, nsym) = R_m(nsym - 1, nsym - 1)$
  - 26: We built  $R_{LD}$  using  $R_m$  based on (Longoria, *et al.*, 2007) and (Bazdresch, *et al.*, 2012)
  - 27:  $row = 1, col = 1$

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28: for  $i = 1$  to  $n_R - 1$  do
29:   for  $j = 1$  to  $n_T - 1$  do
30:     if  $i == j$  then
31:        $R_{LD}(row, col) = R_m(i, j)$ 
32:        $R_{LD}(row + 1, col) = 0.0$ 
33:        $R_{LD}(row, col + 1) = 0.0$ 
34:        $R_{LD}(row + 1, col + 1) = -R_m(i, j)$ 
35:        $col = col + 2$ 
36:     endif
37:     if  $j > i$  then
38:       if  $j \leq n_S$  then
39:          $R_{LD}(row, col) = R_m(i, j)$ 
40:          $R_{LD}(row + 1, col) = 0.0$ 
41:          $R_{LD}(row, col + 1) = 0.0$ 
42:          $R_{LD}(row + 1, col + 1) = -R_m(i, j)^*$ 
43:          $col = col + 2$ 
44:       else
45:          $R_{LD}(row, col) = R_m(i, j)$ 
46:          $R_{LD}(row + 1, col) = R_m(i, j + 1)^*$ 
47:          $R_{LD}(row, col + 1) = R_m(i, j + 1)$ 
48:          $R_{LD}(row + 1, col + 1) = -R_m(i, j)^*$ 
49:          $row = 1$ 
50:          $col = col + 2$ 
50:       endif
51:     endif
52:     if  $j < i$  then
53:        $R_{LD}(row, col) = 0$ 
54:        $R_{LD}(row + 1, col) = 0$ 
55:        $R_{LD}(row, col + 1) = 0$ 
56:        $R_{LD}(row + 1, col + 1) = 0$ 

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57:     col = col + 2
58:   endif
59: endfor
60: endfor
61: We complete  $Q_{LD}$  using  $Q_m$  based on (Kim, et al., 2006) and (Le, et al., 2005)
62: col = 1
63: k = 1 to  $n_S$ 
64:  $Q_{LD}(1:2:2n_R - 1, col) = Q_m(:, k)$ 
65: col = col + 1
66:  $Q_{LD}(2:2:2n_R, col) = Q_m(:, k)^*$ .
67: col = col + 1
68: endfor
69: OUTPUT:  $Q_{LD} = R_{LD}$  and order
70: end
71: end

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The operations required in the estimator, no multiplications are needed but sums, therefore a saving in complexity is achieved without loss of performance in our proposed scheme.

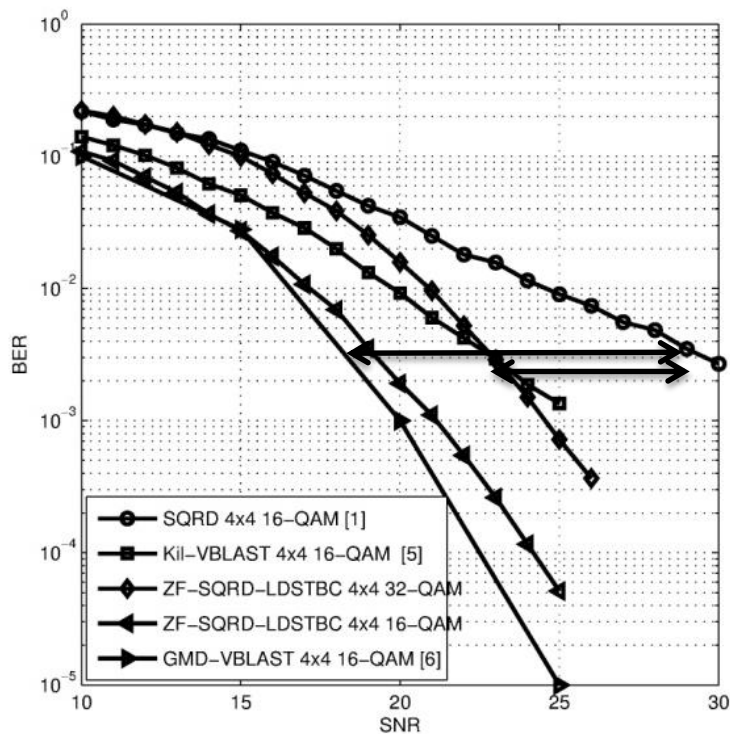
## Simulations Results

### A. BER Performance

To demonstrate the advantages of the proposed scheme, we have performed several simulations to compare the BER performance of different MIMO systems under the mentioned conditions, employing 16-*QAM* and 32-*QAM* modulation schemes. Throughout this paper, the block length is considered fixed to  $L=2$  and all simulations were run until 2000 block-error were found. The BER is represented as a function of the average SNR, where  $N_0 = E_S * n_T / SNR$  and  $E_S$  is the average symbol energy. Figure 2 shows the BER performance comparison between *SQRD* (Wubben, *et al.*, 2001), *KIL-BLAST* algorithm (Raza, *et al.*, 2004), *GMD-VBLAST* (Jiang, *et al.*,

2005) and our proposal ZF-SQRD-LSTBC with  $n_R = 4$  and  $n_T = 4$ . In Table II, we show the spatial data rate for the different schemes evaluated in this work.

As can be seen from Figure 2, the proposal improves around 7.5dB and 10.5dB with respect to that of SQRD when 32-QAM and 16-QAM are used, respectively for a  $BER = 3e^{-03}$ , this performance was achieved without necessity of knowing any information of the CSI neither increase the complexity of the algorithm. In respect to *KIL-BLAST* we have achieved almost 4dB of improve for a  $BER = 1e^{-03}$ . As shown, *GMD-BLAST* outperforms around of 4dB at the proposal when 32-QAM modulation is used, and 1.3dB for a 16-QAM modulation, but this gain has a penalty, a high complexity in both sides of the scheme, also it needs to know CSI to operate. For this reason, we can highlight that the scheme proposal increases considerably the performance of *SQRD*, maintaining the complexity, and easily of detection of the same, therefore, we have considered that *ZF-SQRD-LDSTBC* is a scheme that can be efficiently implemented in hardware.



**Fig. 2.** Bit-error rate of different systems.

**Table II.** Spatial Code Rate.

SCHEME	DATA RATE
SQRD 4x4 16-QAM	16
KIL-BLAST 4x4 16-QAM	12
GMD-VBLAST 4x4 16-QAM	16
ZF-SQRD-LDSTBC 4x4 16-QAM	12
ZF-SQRD-LDSTBC 4x4 32-QAM	15

## B. Complexity analysis

To compare the complexity for the different schemes, we only have considered the number of arithmetical operations necessary to obtain the  $QR$  decomposition. Besides, we have assigned 1 *flop* per sum or multiplication of real numbers executed for the algorithms, and for the square-root and divisions we took the number of *flops* assigned in (Bazdresch, *et al.*, 2012), which are 8 flops per division of real numbers, and 30 *flops* for the square root. The results for schemes of different size are presented in table III.

**Table III.** Complexity comparison.

SCHEME	Number of additions/multiplications of real numbers
SQRD 4x4	320/628
SQRD 6x6	1152/1728
KIL-BLAST 4x4	272/600
KIL-BLAST 6x6	972/1548
ZF-SQRD-LDSTBC 4x4	240/539
ZF-SQRD-LDSTBC 6x6	984/1471

As might be seen, our proposal improves around twenty percent with respect to the scheme proposed in (Wubben, *et al.*, 2001). This improvement is mainly due to the use of the estimator for the energy in the order detection. With respect to *KIL-BLAST*, the complexity to calculate the  $QR$  decomposition is the same to our proposal.



## Conclusions

In this work we have presented the *ZF-SQRD-LDSTBC* hybrid space-time codes, along with a receiver algorithm with very low complexity. This receiver, is based on the theory of linear dispersion codes (Hassibi, Hochwald, 2002), it might be implemented in hardware with CORDIC using Givens rotations. The results showed that the BER performance of these codes is better than other purely spatial codes with the same spatial code rate that have been proposed recently (A. Raza, et. al, 2004), including without feedback required. We also have proposed a method to transmit with the same power all the symbols.

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