An Efficient Detector for STBC-VBLAST Space-Time Code for MIMO Wireless Communications

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Abstract

Hybrid MIMO communication systems are defined as a combination of architectures designed to achieve both multiplexing gain (such as VBLAST), and diversity gain, (such as STBC) such that transmission schemes that have both high spectral efficiency and link reliability can be developed. In this paper we introduce a new way to represent hybrid systems, in which the detection process is carried out in a unified manner for both spatial and diversity transmitted symbols, using an OSIC algorithm, but symbol by symbol, just as single VBLAST systems performs. In this paper we present an efficient and low-complexity, ordered, successive interference cancellation receiver based on sorted QR decomposition for the hybrid STBC-VBLAST transmission scheme. We show how the use of our detection scheme proposal outperforms other recent hybrid detection schemes in terms of bit error rate, even when there is precoding at the transmitter. We also show our proposal has lower complexity, achieved by exploiting the structure of the linear dispersion matrices. [1]

1 Introduction

The demand for communication systems that effectively exploit the wireless channel's limited capacity [10] has grown rapidly 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 raising 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. Two general techniques have been devised to take advantage of MIMO systems: *Spatial Multiplexing* and *Diversity Transmission*. The first technique aims to increase the number of available transmit channels; one of its main proponents are *Vertical Layered Space-Time Codes*, also known as V-BLAST (*Bell-Labs Architecture for Space-Time*), which were first introduced in [4]. Its most interesting attributes are a very high spectral efficiency, ease of code design and comparatively simple receiver architectures; their performance is highly dependent on the channel statistics such as the spatial correlation between antennas at the receiver and transmitter ends. The second technique has the goal of increasing diversity gain; this was achieved by the *Space-Time Block Codes* (STBC) [9]. Implementing STBC decoders is a tractable problem, but they have the disadvantage that their spectral efficiency is low. A popular scheme that reaches full-diversity and full-rate was proposed in a seminal work by Alamouti [1]. In [14], it was proved that MIMO systems exhibit a fundamental trade-off between spectral efficiency and link quality. In this sense, V-BLAST and orthogonal STBCs represent two extremes of this trade-off.

It is also possible to design systems with both spatial and multiplexing gains. For example, linear dispersion codes [5] may be designed to optimize the trade-off between the two gains. They take advantage of the structure of the system equation to use ordered successive interference cancel-

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lation (OSIC) decoding, which means they retain the simplicity of VBLAST. One possible approach, known as hybrid coding [3, 2, 7, 13, 8], consists in the selection of some of the available transmit antennas to work in STBC mode, while the remaining ones operate as V-BLAST. In [3], we proposed a hybrid scheme called *ZF-SQRD-LQOSTBC*. It consists of any number of ABBA encoders of 3 of 4 antennas [11], and any number of V-BLAST antennas, and any number of ABBA encoders of 3 or 4 antennas each. In this paper, we extended this work at the transmission scheme STBC-VBLAST proposed in [7], we show how to transform the original system equation for the scheme STBC-VBLAST as a particular LD code. we derive the system's linear dispersion matrices for this schemes, that which allows a simple OSIC detector to be used in the detection process. We called our proposal receiver scheme *ZF-SQRD-LDSTBC*. Then, we exploit the matrices' structure to obtain a low-complexity receiver algorithm based on the sorted QR decomposition [12]. BER performance is further increased by allocating the same energy to each transmitted symbol, in contrast to other recent proposals where equal power is allocated to each antenna.

We compare, by means of computer simulations, our proposal's BER performance and receiver complexity to the receiver schemes for STBC-VBLAST architectures presented in [7, 8, 13]. We show in this paper that our proposal receiver outperforms these three recent receiver architectures and has lower complexity, without requiring CSI at the transmitter.

2 System Model

2.1 Channel Model

We consider a communications system with n_T and n_R transmit and receive antennas, respectively. All transmit antennas draw symbols from the same *M-QAM* constellation, share the same frequency band and transmit symbols in unison. The Channel State Information (CSI) of the MIMO channel is known at the receiver side and to be perfectly synchronized. The $n_R \times n_T$ channel matrix H contains samples from a complex, i.i.d. zero-mean Gaussian random variables with variance $\sigma_h^2 = 0.5$ per dimension. Assuming flat fading conditions, the elements of H are constant during a transmitted block of length L and vary from one block to another independently. In addition, the channel adds additive white Gaussian noise with variance $\sigma_n^2 = \frac{N_0}{2}$ per dimension to each received symbol.

2.2 Transmitter Architecture

A simplified block diagram of the *ZF-SQRD-LDSTBC*system based on the scheme proposed in [7] is depicted in Figure 1.

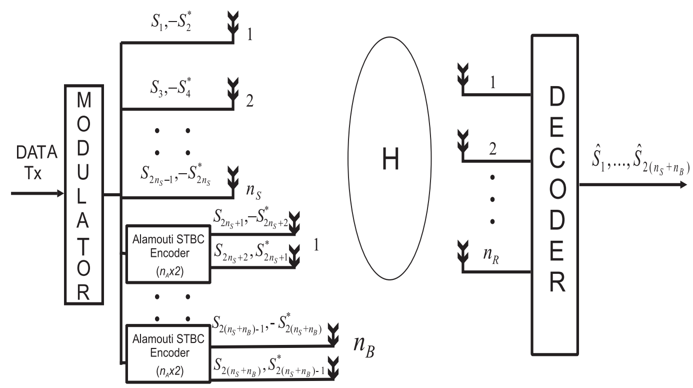

Figure 1: ZF-SQRD-LDSTBC Architectute Transmitter/Receiver

Table 1: *ZF-SQRD-LDSTBC* Symbol to Antenna Mapping with $k = B - 1 + n_S$

	Spatial Antennas	STBC Blocks $B = 1, \cdots, n_B$	
Time	Antenna $V = 1, 2, \cdots, n_S$	Antenna 1	Antenna 2
t	s_V	s_{kn_A+1}	s_{kn_A+2}
$t+T$	$-s^*_{V+1}$	$-s^*_{kn_A+2}$	$s^*_{kn_A+1}$

A single data stream is demultiplexed into n_L spatial layers, and each of them is mapped to the constellation chosen. The symbol mapping fed two different kind of transmitters: n_S VBLAST layers and n_B STBC encoders with $n_A = 2$ antennas each one, therefore $n_T = n_S + 2n_B$. It is assumed that $n_R \geq n_S + n_B$. In the transmission of one block, the symbol sequence $s_1, s_2, \cdots, n_{nsym}$, where $n_{sym} = 2(n_S + n_B)$ is transmitted. The mapping of symbols to antennas is shown in Table 1. The fraction of power allocated to the V-BLAST layers is given by $P_S = \frac{m}{2(n_S+n_B)}$, and the fraction allocated to the ABBA encoder is given by $P_A = \frac{P_S}{2n_B}$. This allocation results in all symbols being transmitted with the same power.

2.3 Receiver Architecture

Under the asumption of CSI is perfectly known by the receiver and presence of Gaussian noise, the detection and decoding process of the transmitted signal vector S, at the m^{th} time block slice, where $m = 1, 2$ and $n_A = 2$, the receive signal can be written as:

$$\begin{bmatrix} y_1^{(1)} & y_1^{(2)} \\ y_2^{(1)} & y_2^{(2)} \\ \vdots & \vdots \\ y_{n_R}^{(1)} & y_{n_R}^{(2)} \end{bmatrix} = \begin{bmatrix} h_{1,1} & \cdots & h_{1,n_T} \\ h_{2,1} & \cdots & h_{2,n_T} \\ \vdots & \ddots & \vdots \\ h_{n_R,1} & \cdots & h_{n_R,n_T} \end{bmatrix} \begin{bmatrix} S_{spa} \\ S_A \end{bmatrix} + \begin{bmatrix} n_1^{(1)} & n_1^{(2)} \\ n_2^{(1)} & n_2^{(2)} \\ \vdots & \vdots \\ n_{n_R}^{(1)} & n_{n_R}^{(2)} \end{bmatrix}, \quad (1)$$

or, equivalently,

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

In (1) an the following equations, the subindices indicate the correspondent antenna number, and superindices indicate symbol period within a block emission time.

Matrix $Y \in \mathcal{C}^{n_R \times 2}$ represents the symbols received in a block. Matrix H is the channel matrix defined above. Matrix $N \in \mathcal{C}^{n_R \times 2}$ represents the noise added to each received symbol. Matrix S is composed for two blocks: The matrix S_{spa} corresponds to the symbols transmitted by VBLAST layers and the matrix S_A to the symbols transmitted by STBC encoders.

The spatial multiplexing block S_{spa} is defined as:

$$S_{spa} = \begin{bmatrix} s_1 & -s_2^* \\ s_3 & -s_4^* \\ \vdots & \vdots \\ s_{2n_S-1} & -s_{2n_S}^* \end{bmatrix} = \begin{bmatrix} s_1^{(1)} & s_1^{(2)} \\ s_2^{(1)} & s_2^{(2)} \\ \vdots & \vdots \\ s_{n_S}^{(1)} & s_{n_S}^{(2)} \end{bmatrix}, \quad (3)$$

and the STBC block is defined as:

$$S_A = \begin{bmatrix} S_1^A \\ \vdots \\ S_{n_B}^A \end{bmatrix} = \begin{bmatrix} S_1^{(1)A} & S_1^{(2)A} \\ \vdots & \vdots \\ S_{n_B}^{(1)A} & S_{n_B}^{(2)A} \end{bmatrix}, \quad (4)$$

where every element of equation (4) is given by:

$$\begin{bmatrix} S_B^{(1)A} & S_B^{(2)A} \end{bmatrix} = \begin{bmatrix} s_{kn_A+1} & -s_{kn_A+2}^* \\ s_{kn_A+2} & s_{kn_A+1}^* \end{bmatrix},$$

with $B = 1, 2, \cdots, n_B$ and $k = B - 1 + n_S$. In equations (3), (4), the matrix on the left is a direct mapping from Table (1); the notation of the matrix on the right, where antenna number and symbol period are made explicit, is adopted to simplify the explanation of the receiver algorithm.

Reformulating the system equation (1) as a linear dispersion code [5], we have:

$$\begin{bmatrix} y_1^{(1)} \\ y_1^{(2)^*} \\ \vdots \\ y_{n_R}^{(1)} \\ y_{n_R}^{(2)^*} \end{bmatrix} = \begin{bmatrix} H_{spa} & H_A \end{bmatrix} S_{LD} + \begin{bmatrix} n_1^{(1)} \\ n_1^{(2)^*} \\ \vdots \\ n_{n_R}^{(1)} \\ n_{n_R}^{(2)^*} \end{bmatrix}. \quad (5)$$

The equation (5) can be expressed in compact form as:

$$Y_{LD} = H_{LD} S_{LD} + N_{LD}, \quad (6)$$

where H_{LD} composed of two blocks is named Linear Dispersion Matrix, one corresponding to the VBLAST layers and another to the STBC layers. The VBLAST block H_{spa} is given by:

$$H_{spa} = \begin{bmatrix} H_{1,1}^{spa} & H_{1,2}^{spa} & \cdots & H_{1,n_S}^{spa} \\ H_{2,1}^{spa} & H_{2,2}^{spa} & \cdots & H_{2,n_S}^{spa} \\ \vdots & \vdots & \ddots & \vdots \\ H_{n_R,1}^{spa} & H_{n_R,2}^{spa} & \cdots & H_{n_R,n_S}^{spa} \end{bmatrix}, \quad (7)$$

where

$$H_{ij}^{spa} = \begin{bmatrix} h_{i,j} & 0 \\ 0 & -h_{i,j}^* \end{bmatrix}, \quad (8)$$

for $i = 1, 2, \cdots, n_R$ and $j = 1, 2, \cdots, n_S$. The STBC block H_A is itself a block matrix; it is given by:

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

where every element of equation (9) is given by:

$$H_{kB}^A = \begin{bmatrix} h_{k,2B+n_S-1} & h_{k,2B+n_S} \\ h_{k,2B+n_S}^* & -h_{k,2B+n_S-1}^* \end{bmatrix}, \quad (10)$$

for $k = 1, 2, \cdots, n_R$ and $B = 1, 2, \cdots, n_B$. The matrix H_{ij}^{spa} is the portion of H_{LD} that links the j^{th} spatial antenna with the i^{th} receiver antenna. Likewise, H_{kB}^A links the B^{th} STBC block to the k^{th} receiver antenna. A matrix structure similar to (9) is shown in [6]. To complete the reformulation of system equation (2), it remains to rearrange matrix S. We define S_{LD} as:

$$S_{LD} = \begin{bmatrix} S_{LD}^{spa} \\ S_{LD}^A \end{bmatrix}, \quad (11)$$

where

$$S_{LD}^{spa} = \begin{bmatrix} s_1^{(1)} \\ s_1^{(2)} \\ \vdots \\ s_{n_S}^{(1)} \\ s_{n_S}^{(2)} \end{bmatrix}, \quad (12)$$

and

$$S_{LD}^{A} = \begin{bmatrix} S_1^{(1)A} \\ \vdots \\ S_{n_B}^{(1)A} \end{bmatrix}. \qquad (13)$$

The reformulation of equation (1) as equation(5) allows to consider to Hybrid MIMO system as an with a simpler, equivalent purely spatial system with $n_{sym} = 2(n_S + n_B)$ transmit antennas and without distinction between the STBC and VBLAST layers. In this way, we are now ready to propose a receiver algorithm based on the sorted-QR decomposition and OSIC linear detection that takes advantage of the structure of the linear dispersion matrices to achieve low complexity and high performance.

3 *ZF-SQRD-LDSTBC* Decoding Process

Matrix H_{LD} is $2n_R{\times}2(n_S{+}n_B)$. A direct application of the Modified Gram-Schmidt on it would result in unacceptable complexity. However, taking advantage of the structure that shows the matrix H_{LD} by the proposed code, we can decrease this complexity significantly. We now explain how this reduction in the complexity is achieved. The general idea of the proposal method is to calculate $H = Q_m R_m$ using the original sorted QR decomposition, and after use Q_m and R_m to built Q_{LD} and R_{LD}, this is possible because many of the elements of each matrix are equal, and their row and column are fixed and can be calculated in advance. Specifically, using Q_m and R_m, non normalized columns $l+1$ and $l+3$ with $l = 2(n_S + B - 1)$ of Q_{LD} of STBC block are determined. The next step is analogous to MGS: column $l{+}1$ is normalized and used to fill column $l{+}2$; the process is repeated for the remaining columns of all STBC blocks.

In the process, matrix R_{LD} is also calculated. Our algorithm is presented in two parts. Algorithm 1 takes the channel matrix H and outputs three intermediate matrices and permutation vector $order$. Algorithm 2 takes the intermediate matrices and derives the final matrices Q_{LD} and R_{LD}. The STBC layers are decoded first, to increase diversity. In OSIC, the column norms of the channel matrix determine detection order. To further decrease complexity, with negligible effect on BER, we use an estimate of the vector norm given by

$$\|x\|_{est} = sum[|\Re(x))|] + sum[|\Im(x)|].$$

Algorithm 1 *ZF-SQRD-LDSTBC* Modified SQRD

Entrada: $H^{n_R \times n_T}$, L, $nsym$, n_S.
Salida: Q_m, R_m, $order$, Q_{LD}^A, R_{LD}^A
$Q_m = H$, $R_m^{n_T \times n_T} = 0$, $order = [1:1:nsym]$.
QR Decomposition of the VBLAST layers:
for $i = 1$ to n_S **do**
  $k = \text{argmin}_{j=i:n_S} \|(Q_m(:,j))\|_{est}$
  exchange columns i and k of Q_m and R_m.
  exchange columns $Li : -1 : i(L-1)+1$ and columns $Lk : -1 : k(L-1)+1$ of $order$
  $R_m(i,i) = \|Q_m(:,i)\|_2$
  $Q_m(:,i) = Q_m(:,i)/R_m(i,i)$
  for $j = i+1$ to n_T **do**
    $R_m(i,j) = Q_m(:,i)^* Q_m(:,j)$
    $Q_m(:,j) = Q_m(:,j) - Q_m(:,i) R_m(i,j)$
  end for
end for
QR Decomposition of the STBC layers:
$col = n_S + 2$
for $i = 1$ to n_B **do**
  $Q_{LD}^A(1:2:2n_R-1, 2*i-1) = Q_m(:, col-1)$
  $Q_{LD}^A(2:2:2n_R, 2*i-1) = Q_m(:, col)^*$
  $Q_{LD}^A(1:2:2n_R-1, 2*i) = Q_m(:, col)$
  $Q_{LD}^A(2:2:2n_R, 2*i) = Q_m(:, col-1)^*$
end for
for $i = 1:2$ to $2n_B$ **do**
  $k = \text{argmin}_{j=i:2:2n_B} \|Q_{LD}^A(:,j)\|_{est}$
  exchange columns $k, k+1$ and $i, i+1$ of Q_{LD}^A and R_{LD}^A.
  exchange columns $n_R + Li : -1 : n_R + i(L-1)+1$ and $n_R + Lk : -1 : n_R + k(L-1)+1$ of *order*
  $R_{LD}^A(i,i) = \|Q_{LD}A(:,i)\|$
  $Q_{LD}^A(:,i) = Q_{LD}^A(:,i)/R^{div}(i,i)$
  $R^{div}(i+1,i+1) = -R_{LD}^A(i,i)$
  $Q_{LD}^A(1:2:Ln_R-1, i+1) = -Q_{LD}^A(2:2:Ln_R, i)^*$
  $Q_{LD}^A(2:2:Ln_R, i+1) = Q_{LD}^A(1:2:Ln_R-1, i)^*$
  for $j = i+1$ to $2n_B$ **do**
    $R_{LD}^A(i,j) = Q_{LD}^A(:,i)^* \cdot Q_{LD}^A(:,j)$
  end for
  $R_{LD}^A(i+1, i+2:2:Ln_B-1) = R_{LD}^A(i, i+3:2:Ln_B)^*$
  $R_{LD}^A(i+1, i+3:2:Ln_B) = -R_{LD}^A(i, i+2:2:Ln_B-1)^*$
  for $j = i+2, j = j+2$ to $2n_B$ **do**
    $Q_{LD}^A(:,j) = Q_{LD}^A(:,j) - Q_{LD}^A(:,i) R_{LD}^A(i,j)$
    $Q_{LD}^A(:,j) = Q_{LD}^A(:,j) - Q_{LD}^A(:,i{+}1) R_{LD}^A(i{+}1,j)$
  end for
end for

Algorithm 2 Obtain Q_{LD} and R_{LD} from Q_m,R_m, Q_{LD}^A and R_{LD}^A

Input: Q_m, R_m, Q_{LD}^A and R_{LD}^A.
Output: Q_{LD}, R_{LD}.
Let $R_{LD}^{2n_R \times 2(n_S+nB)} = 0$.
Built Q_{LD}^{vblast} from Q_m:
$col = 1$
for $k = 1$ to n_S **do**
    $Q_{LD}^{vblast}(1 : 2 : 2n_R - 1, col) = Q_m(:, k)$
    $col = col + 1$
    $Q_{LD}^{vblast}(2 : 2 : 2n_R, col) = -Q_m(:, k)^*$
    $col = col + 1$
end for
Built R_{LD}^{spa} and R_{LD}^A from R_m and R_{LD}^A respectively:
$row = 1$
for $k = 1$ to n_S **do**
    $R_{LD}^{vblast}(row, 1 : 2 : 2n_S - 1) = R_m(k, 1 : n_S)$
    $R_{LD}^{vblast}(row + 1, 2 : 2 : 2n_S) = -R_m(k, 1 : n_S)^*$
    $row = row + 2$
end for
$row = 1$, $col = 2n_S + 1$
for $i = 1$ to $n_S + n_B$ **do**
    for $j = 1$ to n_B **do**
        $R_{LD}^{vblast}(row, col) = R_m(i, 2j - 1 + n_S)$
        $R_{LD}^{vblast}(row, col + 1) = R_m(i, 2j + n_S)$
        $R_{LD}^{vblast}(row + 1, col) = R_m(i, 2j + n_S)^*$
        $R_{LD}^{vblast}(row + 1, col + 1) = -R_m(i, 2j - 1 + n_S)^*$
        $col = col + 2$
    end for
    $col = 2n_S + 1$
    $row = row + 2$
end for
$R_{LD}^A(2*n_S+1 : 2*(n_S+n_B), 2*n_S+1 : 2*(n_S+n_B)) = R_{LD}^A$
$R_{LD} = \begin{bmatrix} R_{LD}^{vblast} \\ R_{LD}^A \end{bmatrix}$,
$Q_{LD} = [Q_{LD}^{vblast} \quad Q_{LD}^A]$

4 Results

To demonstrate the advantages of the proposed detector for the scheme *ZF-SQRD-LDSTBC*, we compare the Bit Error Rate (BER) performance of the different detector for the hybrid MIMO system over the mentioned conditions, employing $8 - PSK$ and *16-QAM* modulation schemes. Through this paper, the block length is fixed to $L = 2$ and all simulations were run until 500 block-errors 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.

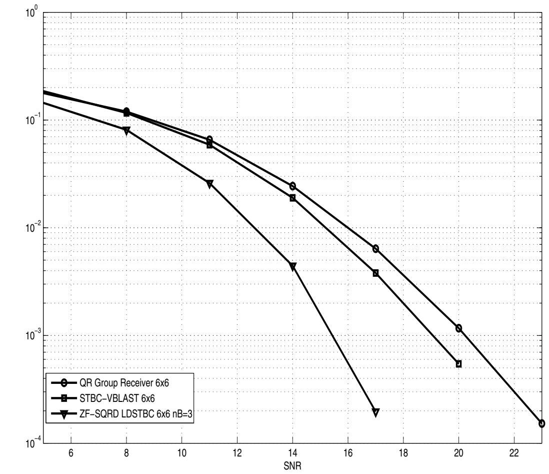

Figure 2: BER vs. average SNR of *ZF-SQRD-LDSTBC*, STBC-VBLAST6 $\times$ 6 $(2, 2, 3)$ [7], and QR Group Receiver 6×6 [13].

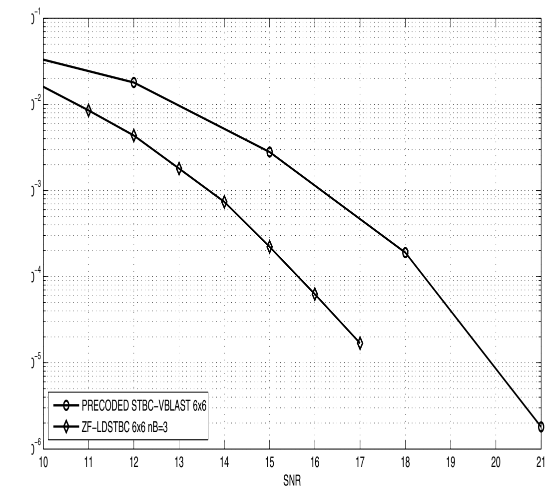

Figure 3: BER vs. SNR of *ZF-SQRD-LDSTBC* and Precoded STBC-V-BLAST [8].

In Fig. (2), we show the BER performance comparison between QR Group Receiver 6×6 [13], STBC-VBLAST algorithm 6×6 $(2, 2, 3)$ [7], and our proposal with $n_R = 6$, $n_T = 6$ and $n_B = 3$. In all cases, the code rate has been fixed to 3 symbols (12 bits) transmitted per channel use. With $n_T = 6$ and $n_R = 6$ and $n_B = 3$, at BER$= 10^{-4}$, *ZF-SQRD-LDSTBC* outperforms [13] and [7] by 2.75dB and 1.2dB, respectively. *ZF-SQRD-LDSTBC* still maintains lower complexity.
In Fig. 3, we compare *ZF-SQRD-LDSTBC* with a precoded hybrid code [8]. This code requires CSI at the transmit-

Table 2: Spectral Efficiency Comparison

Scheme	*Spatial Data Rate (bps/Hz)*
STBC-VBLAST *16-QAM*	12
QR-GROUP RECEIVER *16-QAM*	12
Precoded STBC-VBLAST *8-PSK*	8.25
ZF-SQRD-LDSTBC 16-QAM	12
ZF-SQRD-LDSTBC 8-PSK	9

Table 3: Complexity comparison

Scheme	Number of real additions/multiplications
STBC-V-BLAST (2,2,2) 6×6 [7]	$1092/1668$
QR Group Receiver 6×6 [13]	$972/1548$
ZF-SQRD-LDSTBC 6×6	$1029/648$

ter, which is used to optimally allocate antenna power. 3 symbols per channel use requires a precoded system of size 6×6. Without CSI and the extra cost of precoding, *ZF-SQRD-LDSTBC* with use 6 antennas per side outperforms the precoded system by 2dB for a BER$= 10^{-4}$.
In Table 2, we show the spatial data rate for the different schemes evaluated in this work. Analyzing Fig. 2, Fig. 3 and Table 2, we can said that the proposed scheme in this work, achieves better trade-off among diversity and spectral efficiency than the systems referred in [7], [14] and [8]. The notation used in every antenna configuration is the same as the handled in [7].

4.1 Complexity analysis

We present a complexity comparison between our proposal, QR Group Receiver 6×6, and STBC-VBLAST (2,2,3) 6×6. We compare the number of real additions and multiplications required, operating at 3 symbols per channel use with *16-QAM* modulation. *ZF-SQRD-LDSTBC* with $n_T = n_R = 6$ requires around 30% and 33% less operations than [13] and [7]; with $n_T = n_R = 6$, *ZF-SQRD-LDSTBC* still requires between 31% and 39% less operations.

5 Conclusions

We have presented a new hybrid MIMO space-time code with arbitrary number of STBC and spatial layers, and a receiver algorithm with very low complexity. We have used the theory of linear dispersion codes to transform the original MIMO system to an equivalent system where the OSIC method for nulling and cancellation of the interference among layers can be applied. Compared with other recent hybrid codes, our proposal achieves better performance in terms of bit error rate, even without CSI at the transmitter, and lower complexity.

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