An Efficient Architecture for Detection of Linear Dispersion Space-Time Codes Based on QR Decomposition

Cortéz G. Joaquín, Pizarro L. Andrés O. and Domitsu K. Manuel

***Abstract*— A novel architecture for detection of Linear Dispersion Space-Time Codes (LDSTBC) over Rayleigh fading channels is presented. The LDSTBC scheme consists of one Alamouti space-time block code unit, plus two more antennas operating as two layers as V-BLAST unit in the transmitter. The LDSTBC receiver can be operate with three or more antennas simultaneously. The proposed receiver is based on an Ordered Successive Interference Cancellation (OSIC) scheme and the *QR* decomposition, which leads to a suitable hardware implementation. It was designed for Zero-Forcing (ZF) criterion; reduced complexity is achieved by means of an adequate rearrangement of the channel matrix elements. The detection scheme proposed is evaluated and compared with other similar recently reported proposal, assuming a channel without spatial correlation.**

***Keywords*— MIMO systems, Linear Space-Time Codes Layered Space-Time Block Codes, *QR* decomposition**

I. INTRODUCTION

The demand for communication systems that effectively exploit the wireless channel's limited capacity [1] 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 techniques have been developed 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 [2]. Their most interesting attributes are a very high spectral efficiency, ease of code design and comparatively simple receiver architectures; their performance is highly dependent of 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) [3]. Implementing STBC decoders is relatively easy to carry out, 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 [4].

Based on these techniques, a kind of space-time codes called *linear dispersion space-time codes* was presented in [5]; these codes are proposed as a very simple way to simultaneously obtain transmitter diversity and spatial multiplexing gain. The objective of our work is to introduce a detection scheme for this kind of codes.

We refer to this new architecture as *ZF-QR-OSIC-LDSTBC*, since the receiver is based on an *Ordered Successive Interference Cancellation* (OSIC) scheme and on the *QR* decomposition, and it uses the *Zero-Forcing* criterion [6]. We rearrange the elements of the channel matrix H in order to simplify its *QR* decomposition, and avoid calculating any matrix pseudo-inverse in the estimation and detection of the transmitted symbols. Symbols exhibiting diversity gain are detected first, followed by the spatially-multiplexed symbols. We show, by means of computer simulations, that the proposed scheme is capable of achieving similar performance with fewer antennas than other similar and recently proposed algorithms [7], [8], [9].

The outline of the paper is the following: Section II details the channel model under consideration. Section III contains an in-depth explanation of the proposed architecture and the detection algorithm. Section IV presents the detection algorithm proposed, in the section V we analyzes the simulation results; our conclusions are presented in section VI.

II. CHANNEL MODEL

A. Rayleigh Fading Channel

It is assumed that the propagation channel between each pair of transmit and receive antennas can be modeled as a Rayleigh narrowband stationary stochastic process. We also consider that the channel is scatterers-rich at both the transmitter and receiver sides. For simulation, a realization

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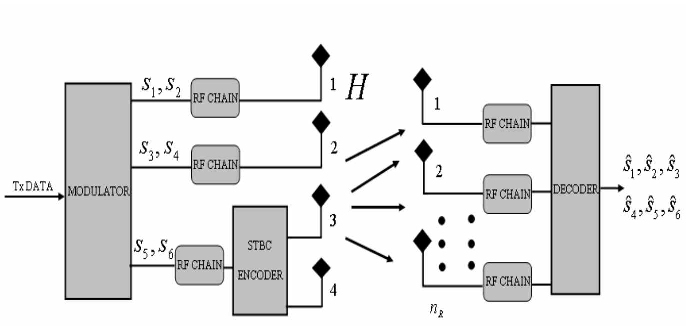

Fig. 1. ZF-QR-OSIC LDSTBC Transmitter/Receiver.

of the MIMO channel can be expressed as a random matrix H of size $N_R \times n_T$, where n_T and n_R are the number of antennas at the transmitter and receiver, respectively. The elements of H are denoted h_{ij}, for i=1, 2,…,n_R, j=1, 2, …,n_T. With the propagation model considered, each entry of H at any time is a complex Gaussian random variable with zero mean and variance 0.5 per dimension. We assume that the temporal channel fading is slow compared with the symbol period T, and thus a quasi-static block fading model is enough to characterize the temporal correlation; therefore, the channel matrix H is randomly generated, but remains constant during the transmission of one space-time code word of length 2T. A new realization of the channel matrix, independent of the previous one, is then generated for each new space-time code word.

III. System Model

A. Linear Dispersion Space-Time Codes

The general structure of a linear dispersion code assume that the system have n_T transmit antennas, n_R receive antennas and where a set of Q symbols taken from a *r-QAM* constellation, are send through of the n_T transmit antennas during T symbols period. The allocation in space and time of the transmitted symbols is specified in the transmission matrix S.

The linear dispersion code for the matrix S can be defined by the next equation:

$$S = \sum_{i=1}^{Q} \left(\alpha_q A_q + j\beta_q B_q \right), \quad (1)$$

Where the real scalars $\{\alpha_q, \beta_q\}$ are given by $s_q = \alpha_q + j\beta_q$, for $q = 1,2,\ldots,Q$. The code is completely specified by the fixed $T \times n_T$ complex matrices $A_1,\ldots,A_Q$ and $B_1,\ldots,B_Q$.

B. QR-OSIC LDSTBC Transmitter

In general, the transmission process of a *linear dispersion space-time codes* scheme can be divided in layers, like V-BLAST. However, in contrast to V-BLAST, these schemes may consist of a stream of symbols at the output of an Alamouti STBC encoder [4], which is sent to a group of antennas, or of an uncoded stream, which is transmitted from a single antenna. The basic idea behind these structures is to combine array processing and space-time coding, as presented in [10]. We propose a *linear dispersion space-time code* MIMO transceiver, whose structure is shown in Fig. 1.

Table I. Antenna Mapping for *LDSTBC* Scheme

Time	Antenna 1	Antenna 2	Antenna 3	Antenna 4
t	s_1	s_3	s_5	s_6
$t+1$	$-s_2^*$	$-s_4^*$	$-s_6^*$	s_5^*

It employs four elements to transmit with three spatial multiplexing layers. In the first two layers one spatially multiplexed antenna is used in each layer, while in the third layer an Alamouti STBC encoder is used. Three or more antennas may be used in the receiver. As can be inferred from Fig. 1, we consider a MIMO system consisting of n_T=4 transmit antennas and $n_R \geq 3$ receive antennas. The input bit stream is mapped to symbols using a *QAM-16* modulator. For the purposes of simplification we assume that all the antennas transmit information symbols from the same constellation map, also we assume that the receiver is perfectly synchronized. The channel is modeled as H , where each element h_{ij} is the complex transfer function from transmitter j to receiver i. The receiver is assumed to know H perfectly. Also, it is assumed that H is full-rank. The total transmitted power is normalized to 1 watt.

During two symbol periods, the sequence of symbols $\{s_i\}_{i=1}^{6}$ is transmitted and multiplexed over the four antennas as shown in Table I; therefore, we can write the system equation for the case when $n_T=4$ and $n_R=4$, over two symbol periods, as:

$$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \\ y_{31} & y_{32} \\ y_{41} & y_{42} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} s_1 & -s_2^* \\ s_3 & -s_4^* \\ s_5 & -s_6^* \\ s_6 & s_5^* \end{bmatrix} + \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \\ n_{31} & n_{32} \\ n_{41} & n_{42} \end{bmatrix}, \quad (2)$$

or, equivalently,

$$Y = HS + N, \quad (3)$$

where y_{it} and n_{it} are the received signal and noise, respectively, in the instant t for the receiver antenna i. The noise samples n_{it} are i.i.d. complex Gaussian random variables with zero mean and variance σ_n^2.

From equation (2), it can be seen that six information symbols (two from each multiplexed layer) are transmitted in 2T consecutive channel uses.

C. ZF-QR-OSIC LDSTBC as linear dispersion space-time code

The transmission matrix S for *ZF-QR-OSIC LDSTBC* can be specified by the next dispersion matrices $A_1,\ldots,A_Q$ and $B_1,\ldots,B_Q$ for $q = 1,2,\ldots,Q$, $T=2$, $n_T=4$ and $n_R=4$.

$$A_1 = \begin{bmatrix} 1\,0\,0\,0 \\ 0\,0\,0\,0 \end{bmatrix} \quad A_2 = \begin{bmatrix} 0\,0\,0\,0 \\ -1\,0\,0\,0 \end{bmatrix} \quad A_3 = \begin{bmatrix} 0\,1\,0\,0 \\ 0\,0\,0\,0 \end{bmatrix} \quad A_4 = \begin{bmatrix} 0\,0\,0\,0 \\ 0\,-1\,0\,0 \end{bmatrix}$$

$$A_5 = \begin{bmatrix} 0\,0\,1\,0 \\ 0\,0\,0\,1 \end{bmatrix} \quad A_6 = \begin{bmatrix} 0\,0\,0\,1 \\ 0\,0\,-1\,0 \end{bmatrix}$$

$$B_1=\begin{bmatrix}1\,0\,0\,0\\0\,0\,0\,0\end{bmatrix}\quad B_2=\begin{bmatrix}0\,0\,0\,0\\1\,0\,0\,0\end{bmatrix}\quad B_3=\begin{bmatrix}0\,1\,0\,0\\0\,0\,0\,0\end{bmatrix}\quad B_4=\begin{bmatrix}0\,0\,0\,0\\0\,1\,0\,0\end{bmatrix}$$

$$B_5=\begin{bmatrix}0\,0\,1\,0\\0\,0\,0\,-1\end{bmatrix}\quad B_6=\begin{bmatrix}0\,0\,0\,1\\0\,0\,1\,0\end{bmatrix}$$

The matrices that generate the symbols of the transmission matrix S satisfies the constraint 1 of the proposed method given in [6].

IV. Detection Algorithm For *ZF-QR-OSIC LDSTBC*

The order of detection using Ordered Successive Interference Cancellation (OSIC) techniques based on the *zero-forcing* solution [6] in V-BLAST systems is very important because an optimum order can reduce the risk of error propagation in the estimation of the transmitted symbols. In [11] a very efficient method to obtain an optimal order based on the QR decomposition of the channel matrix H was proposed, it is presented as an extension to the Modified Gram-Schmidt algorithm [12] by reordering the columns of the channel matrix prior to each orthogonalization step. The principal idea is that $\|r_{k,k}\|^2$ is *minimized* in the order in which are computed (from 1 to n_T) instead of being *maximized* in the order of detection (from n_T to 1). Applying this idea in our proposed scheme for the two layers operating as V-BLAST we have to reorder the columns one and two from H of way that their norms satisfied the next equation:

$$\|H(:,1)\|<\|H(:,2)\|, \tag{4}$$

In [13], a successive interference cancellation scheme using the QR decomposition for the double space-time transmits diversity (DSTTD) system is proposed. We introduce the following difference: by rearranging the elements of the channel matrix H, the QR decomposition may be used to estimate the transmitted symbols. Adjusting this idea to our scheme, we rewrite equations (2) and (3) to obtain (5) and (6):

$$\begin{bmatrix}y_{11}\\y_{12}^*\\y_{21}\\y_{22}^*\\y_{31}\\y_{32}^*\\y_{41}\\y_{42}^*\end{bmatrix}=\begin{bmatrix}h_{11}&0&h_{12}&0&h_{13}&h_{14}\\0&-h_{11}^*&0&-h_{12}^*&h_{14}^*&-h_{13}^*\\h_{21}&0&h_{22}&0&h_{23}&h_{24}\\0&-h_{21}^*&0&-h_{22}^*&h_{24}^*&-h_{23}^*\\h_{31}&0&h_{32}&0&h_{33}&h_{34}\\0&-h_{31}^*&0&-h_{32}^*&h_{34}^*&-h_{33}^*\\h_{41}&0&h_{42}&0&h_{43}&h_{44}\\0&-h_{41}^*&0&-h_{42}^*&h_{44}^*&-h_{43}^*\end{bmatrix}\begin{bmatrix}s_1\\s_2\\s_3\\s_4\\s_5\\s_6\end{bmatrix}+\begin{bmatrix}n_{11}\\n_{12}^*\\n_{21}\\n_{22}^*\\n_{31}\\n_{32}^*\\n_{41}\\n_{42}^*\end{bmatrix}, \tag{5}$$

or equivalently,

$$Y_m=H_mS_m+N_m. \tag{6}$$

In the last expressions, the sub index m stands for *modified*. Note that the elements of the channel matrix have been rearranged in such a way that the QR decomposition leads directly to *OSIC* detection. It is also worthwhile to note that with this method, a change in the number of receiver antennas is straightforward; we need only to add or eliminate the corresponding rows to H.

D. ZF-OSIC based on the QR decomposition (ZF-QR-OSIC-LDSTBC)

We first calculate the QR decomposition [12] of the channel matrix H_m, i.e. $H_m=QR$, where Q is a unitary matrix and R is an upper triangular matrix. By multiplying the received signal (6) by Q^H, the modified received vector is:

$$Y_m=Q^HY_m=RS_m+N_m, \tag{7}$$

if vector S_m is transmitted. Note that the statistical properties of the noise term $N_m=Q^HN_m$ remain unchanged. Due to the upper triangular structure of R, the k-th element of Y_m is:

$$y_k=r_{kk}s_k+\sum_{i=k+1}^{4}r_{ki}s_i+n_k, \tag{8}$$

The symbols are estimated in sequence, from lower stream to higher stream, with successive interference cancellation; assuming that all previous decisions are correct, the interference can be perfectly cancelled in each step except for the additive noise. The estimated symbol $\hat{s}_k$ is given by:

$$\hat{s}_k=D\left[\frac{y_k-\sum_{i=k+1}^{4}r_{ki}\hat{s}_i}{r_{kk}}\right], \tag{9}$$

where $\hat{s}_k$ is the estimate of s_k and $D[\cdot]$ is a decision device that maps its argument to the closest constellation point. We use the Modified Gram-Schmidt (MGS) method [11] to obtain the QR decomposition. In view of the structure of H_m, and that the first two columns of H_m have the same values and are orthogonal, Q and R are simplified to (10), (11):

$$Q=\begin{bmatrix}q_{11}&0&q_{13}&0&q_{15}&-q_{25}^*\\0&-q_{11}^*&0&-q_{13}^*&q_{25}&q_{15}^*\\q_{31}&0&q_{33}&0&q_{35}&-q_{45}^*\\0&-q_{31}^*&0&-q_{33}^*&q_{45}&q_{35}^*\\q_{51}&0&q_{53}&0&q_{55}&-q_{65}^*\\0&-q_{51}^*&0&-q_{53}^*&q_{65}&q_{55}^*\\q_{71}&0&q_{73}&0&q_{75}&-q_{85}^*\\0&-q_{71}^*&0&-q_{73}^*&q_{85}&q_{75}^*\end{bmatrix}, \tag{10}$$

$$R=\begin{bmatrix}r_{11}&0&r_{13}&0&r_{15}&-r_{25}^*\\0&-r_{11}&0&-r_{13}^*&r_{25}&r_{15}^*\\0&0&r_{33}&0&r_{35}&-r_{45}^*\\0&0&0&-r_{33}&r_{45}&r_{35}^*\\0&0&0&0&r_{55}&0\\0&0&0&0&0&r_{55}\end{bmatrix}. \tag{11}$$

Note that the last structure further reduces the complexity

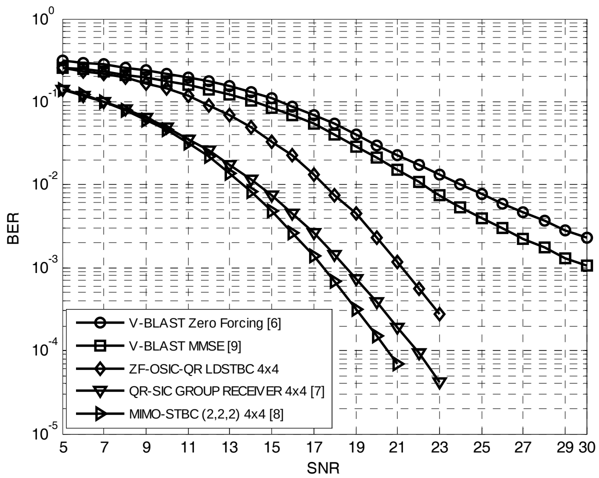

Fig. 2. Bit Error Rate of different MIMO systems.

TABLE II. SPATIAL DATA RATE FOR THE DIFFERENT SCHEMES

V-BLAST Zero Forcing	V-BLAST MMSE	ZF-OSIC-QR-LDSTBC	QR-SIC GROUP RECEIVER	MIMO-STBC
4	4	3	2	2

of the decomposition of the matrix H_m, as it is only necessary to compute three columns of Q and three rows of R (irrespective of the numbers of rows).

From (10) and (11), we can see that the structure of H_m may be exploited to reduce the complexity of the *QR* decomposition. Therefore, we can implement a low complexity *ZF-OSIC* based on the *QR* decomposition (*ZF-QR-OSIC*) for the *LDSTBC* scheme proposed.

V. RESULTS

We compare the performance of the detection schemes in terms of bit error rate (BER) for uncorrelated channels. We use a *QAM-16* modulator. All simulations were run until 2000 frame errors were found. We define the spatial code rate $r_s=N/T$, where N independent symbols are transmitted over T symbol periods, as the average number of independent symbols transmitted from all antennas per symbol period. The receiver is assumed to have perfect channel estimation. Fig. 2 show the obtained BER for the different schemes, including *ZF-QR-OSIC LDSTBC*. In the table II, we show the spatial code rate for the different schemes evaluated in this work. Making an analysis of the figure 1 and the Table II, we can see as the scheme proposal in this work shows a better trade-off between performance and spectral efficiency with respect at schemes based in spatial multiplexing or diversity. For example we observe in the figure as our proposal for BER=2e-03 outperforms with 10dB and 8dB at the schemes purely spatial proposed in [6] and [9]. Exchange with respect at the schemes with diversity proposed in [7] and [8], our proposal shows around 1.25dB and 1.75dB worst for BER=1e-03 respectively, but we achieve a major spectral efficiency with respect these schemes.

In summary, we have proposed a transmission scheme with better trade-off among performance and spectral efficiency complexity, with respect at schemes purely spatial or with diversity. Also the detection scheme proposed is easily scalable and with low complexity and may be more attractive to uses in systems that require high data rate transmission with low power consumption.

VI. CONCLUSIONS

Linear dispersion space-time receivers represent a compromise between diversity and high spectral efficiency. It is interesting note as they allow the possibility of increases the rate of the purely diversity scheme with a penalty in their performance of the system, but with a better behavior with respect at schemes purely spatial. Current power and hardware size requirements dictate that receivers should be as simple as possible and avoid complex operations. We have shown a receiver algorithm that avoids matrix inverses while also reducing the complexity of the *QR* decomposition.

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