Accepted for PIMRC 2005

A CLASS OF FOUR-GROUP QUASI-ORTHOGONAL STBC ACHIEVING FULL RATE AND FULL DIVERSITY FOR ANY NUMBER OF ANTENNAS

Chau Yuen
Nanyang Technological University
Singapore
yuenchau@pmail.ntu.edu.sg

Yong Liang Guan
Nanyang Technological University
Singapore
eylguan@ntu.edu.sg

Tjeng Thiang Tjhung
Institute for Infocomm Research
Singapore
tjhungtt@i2r.a-star.edu.sg

ABSTRACT

We propose and construct a new class of full-rate full-diversity Quasi-Orthogonal Space-Time Block Code (QO-STBC), namely Four-Group QO-STBC (4Gp-QOSTBC), which can support any number of transmit antennas. 4Gp-QOSTBC can linearly separate the symbols into four independent groups, such that symbols within a group is orthogonal to all other symbols in another groups, and the maximum-likelihood (ML) decoder of the code only needs to jointly decode the symbols within the same group. The number of symbols required for joint detection of the newly proposed 4Gp-QOSTBC is half of that required by the existing QO-STBCs with the same code rate, and their full-diversity decoding performances are comparable. We also extend the proposed code construction to obtain 6Gp-QOSTBC and 8Gp-QOSTBC, which have even lower decoding complexity, albeit at a slight loss in code rate.

1. INTRODUCTION

Orthogonal Space-Time Block Codes (O-STBC) has been proposed as a transmit diversity scheme that can provide full transmit diversity with linear decoding complexity [1]. Despite of these advantageous, O-STBC has a code rate that is less than one when more than two transmit antennas and complex constellation are used. Quasi-Orthogonal STBC (QO-STBC) [2-4] with constellation rotation (CR) [5-8] or group-constrained linear transformation [9] have been proposed to provide transmit diversity at a higher code rate than O-STBC. The maximum-likelihood (ML) decoding of QO-STBC can be achieved by jointly detecting a sub-group of the transmitted symbols, rather than all the symbols, hence QO-STBC leads to a lower decoding complexity than general non-orthogonal STBC.

Hence it is of interest to design QO-STBC with low decoding complexity, as a result Minimum-Decoding-Complexity QO-STBC (MDC-QOSTBC) has been designed in [13,14]. MDC-QOSTBC has a simple ML decoding and is only next to O-STBC, i.e. the ML decoding of MDC-QOSTBC only need a joint detection of two real symbols, this is the simplest among all possible non-orthogonal STBCs. But the maximum achievable code rate of MDC-QOSTBC is less than one for more than four transmit antennas.

However, it has been noted in [15] that a full-rate code is desired so as to eliminate the rate-matching problem. Hence in a recent publication [10], a class of full-rate QO-STBC, which can always separate the symbols into two groups and hence perform joint detection of half of the transmitted symbols for any number of transmit antennas, has been proposed. Independently, there is also a rate-one double-symbol decodable Co-ordinate Interleaved Orthogonal Design (CIOD) code for eight transmit antennas [11,12], which can separate the symbols into four groups and hence has a lower ML decoding complexity than the codes of [10]. However, the CIOD design in [11,12] is only suitable for less than eight transmit antennas, and has no general extension to larger number of transmit antennas. In addition, the full-rate CIOD scheme also has a drawback of having large peak-to-average power ratio due to zeros in the transmission matrix [12]. Furthermore, it will be shown later in this paper that the performance of full-rate CIOD will degrade significantly as compared with QO-STBC, when used with less than eight transmit antennas.

In this paper, we propose a new class of QO-STBC with full code rate for any number of transmit antennas, namely Four-Group QO-STBC (4Gp-QOSTBC). The 4Gp-QOSTBC has the property that the symbols received can be separated into four independent groups during the ML decoding process, such that the number of symbols required for joint detection is half of those required in the existing full-rate QO-STBC [3,8,10], which can only separate the transmitted symbols into two groups. Advantages of the 4Gp-QOSTBC over the rate-one double-symbol decodable CIOD code will also be studied.

We will review the signal model of linear STBC and study the design of QO-STBC in Section II and Section III respectively. Next, we construct 4Gp-QOSTBC and investigate its performance in Section IV. We also extend the idea of 4Gp-QOSTBC to 6 / 8Gp-QOSTBC in Section IV. Finally, we will conclude the paper in Section V.

2. LINEAR STBC

Suppose that there are N_t tansmit antennas, N_r receive antennas, and an interval of T symbols during which the propagation channel is constant and known to the receiver. The transmitted signal can be written as a $T \times N_t$ matrix $\mathbf{C}$ that governs the transmission over the N_t antennas during the T symbol intervals. It is assumed that the data sequence has been broken into blocks with K complex symbols, c_1, c_2, …, c_K, in each block for transmission over T symbol periods of time. The code rate of a QO-STBC is defined as $R = K/T$. A STBC $\mathbf{C}$ can be expressed as:

$$\mathbf{C} = \sum_{q=1}^{K} (c_q^{\mathrm{R}} \mathbf{A}_q + j c_q^{\mathrm{I}} \mathbf{B}_q) \quad (1)$$

where the superscript $(\ )^{\mathrm{R}}$ and $(\ )^{\mathrm{I}}$ denotes the real part and imaginary part of a scalar, vector or matrix respectively. The matrices $\mathbf{A}_q$ and $\mathbf{B}_q$ of size $T \times N_t$, for $1 \le q \le K$, are called the "dispersion matrices". The received signal model can then be modeled as [16]:

$$\tilde{\mathbf{r}} = \sqrt{\rho/N_t}\,\mathbf{H}\tilde{\mathbf{c}} + \tilde{\boldsymbol{\eta}} \quad (2)$$

$$\tilde{\mathbf{r}} = \begin{bmatrix} \mathbf{r}_1^{\mathrm{R}} & \mathbf{r}_1^{\mathrm{I}} & \cdots & \mathbf{r}_{N_r}^{\mathrm{R}} & \mathbf{r}_{N_r}^{\mathrm{I}} \end{bmatrix}^{\mathrm{T}},$$

where $\tilde{\mathbf{c}} = \begin{bmatrix} c_1^{\mathrm{R}} & c_1^{\mathrm{I}} & \cdots & c_K^{\mathrm{R}} & c_K^{\mathrm{I}} \end{bmatrix}^{\mathrm{T}}$,

$$\tilde{\boldsymbol{\eta}} = \begin{bmatrix} \boldsymbol{\eta}_1^{\mathrm{R}} & \boldsymbol{\eta}_1^{\mathrm{I}} & \cdots & \boldsymbol{\eta}_{N_r}^{\mathrm{R}} & \boldsymbol{\eta}_{N_r}^{\mathrm{I}} \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{H} = \begin{bmatrix} \mathcal{A}_1\underline{\mathbf{h}}_1 & \mathcal{B}_1\underline{\mathbf{h}}_1 & \ldots & \mathcal{A}_K\underline{\mathbf{h}}_1 & \mathcal{B}_K\underline{\mathbf{h}}_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathcal{A}_1\underline{\mathbf{h}}_{N_r} & \mathcal{B}_1\underline{\mathbf{h}}_{N_r} & \ldots & \mathcal{A}_K\underline{\mathbf{h}}_{N_r} & \mathcal{B}_K\underline{\mathbf{h}}_{N_r} \end{bmatrix},$$

$$\mathcal{A}_p = \begin{bmatrix} \mathbf{A}_p^{\mathrm{R}} & -\mathbf{A}_p^{\mathrm{I}} \\ \mathbf{A}_p^{\mathrm{I}} & \mathbf{A}_p^{\mathrm{R}} \end{bmatrix}, \mathcal{B}_q = \begin{bmatrix} -\mathbf{B}_q^{\mathrm{I}} & -\mathbf{B}_q^{\mathrm{R}} \\ \mathbf{B}_q^{\mathrm{R}} & -\mathbf{B}_q^{\mathrm{I}} \end{bmatrix}, \underline{\mathbf{h}}_i = \begin{bmatrix} \mathbf{h}_i^{\mathrm{R}} \\ \mathbf{h}_i^{\mathrm{I}} \end{bmatrix}.$$

In the above equations, the normalization factor $\sqrt{\rho/N_t}$ is to ensure that the SNR (ρ) at the receiver is independent of the number of transmit antennas. The $\mathbf{r}_i$ and $\boldsymbol{\eta}_i$, for $1 \le i \le N_r$, are $T \times 1$ column vectors which contain the received signal and the zero-mean unit-variance AWGN noise samples for the i^{th} receive antennas over T symbol periods respectively, $\mathbf{h}_i$ is a $N_t \times 1$ column vector that contains N_t Rayleigh flat fading coefficients between the j^{th} transmit to i^{th} receive antenna, $h_{j,i}$, for $1 \le j \le N_t$,.

To quantify for the coding gain of a STBC, [7] has proposed the following diversity product:

$$\varsigma = \frac{1}{2\sqrt{N_t}} \operatorname{Min} \left| \operatorname{Det}\left(\mathbf{A}_{\mathbf{CE}}\right) \right|^{1/(2T)} \quad (3)$$

where $\operatorname{Det}(\mathbf{A}_{\mathbf{CE}})$ is the determinant of the codeword distance matrix.

3. DESIGN OF QO-STBC

The concept of QO-STBC is to divide the K transmitted symbols in a codeword into G independent groups, such that symbols in any group are orthogonal to all symbols in the other groups after appropriate linear processing, such as matched filtering, while strict orthogonality among the symbols within a group is not required [9,13,14]. As a result, the received symbols can be separated into G independent groups by simple linear processing, such that the ML decoding of different groups can be performed separately and in parallel, and the ML decoding of every group can be achieved by jointly detecting only K/G complex symbols that are within the same group [9,13,14]. In addition, it is important to ensure that the QO-STBC can achieve full diversity too. Hence we divide the design of QO-STBC into two parts, one governing the decoding complexity or the grouping of the symbols, the other governing the decoding performance or maximal symbolwise diversity [16,17] of the symbols.

3.1. Algebraic Structure of a QO-STBC

We first review the Quasi-Orthogonal Constraints derived in [9], which formulate the algebraic properties of dispersion matrices of a general QO-STBC.

Definition 1 [9]: A quasi-orthogonal design $\mathbf{C}$ is such that, the equivalent channel matrix, $\mathbf{H}$, as defined in (2) has the property that $\mathbf{H}^{\mathrm{T}}\mathbf{H}$ is block-diagonal and consists of G smaller sub-matrices each with size $(2K/G) \times (2K/G)$.

Theorem 1: The ML decoding of QO-STBC $\mathbf{C}$ as defined in *Definition 1* can be performed by G independent decoders. Each of the decoder only needs to jointly detect $2K/G$ real symbols.

Proof of *Theorem 1*: The decoding of QO-STBC [18] will be summarized as below. A matched filter $\mathbf{H}^{\mathrm{T}}$ can be multiplied to the received signal in (2) to obtain the model in (4).

$$\begin{aligned} \hat{\mathbf{r}} &= \mathbf{H}^{\mathrm{T}}\tilde{\mathbf{r}} \\ &= \sqrt{\rho/N_t}\,\mathbf{H}^{\mathrm{T}}\mathbf{H}\tilde{\mathbf{c}} + \mathbf{H}^{\mathrm{T}}\tilde{\boldsymbol{\eta}} \end{aligned} \quad (4)$$

However, the resultant noise $\mathbf{H}^{\mathrm{T}}\tilde{\boldsymbol{\eta}}$ in (4) will be correlated, this forbids separate decoding of the symbols in different groups even though $\mathbf{H}^{\mathrm{T}}\mathbf{H}$ is block diagonal as defined in *Definition 1*. Hence a whitening filter $\mathbf{H}_{\mathbf{W}}$ can be applied to the matched filter output as shown in (5).

$$\begin{aligned} \bar{\mathbf{r}} &= \mathbf{H}_{\mathbf{W}}\hat{\mathbf{r}} \\ &= \sqrt{\rho/N_t}\,\bar{\mathbf{H}}\tilde{\mathbf{c}} + \bar{\boldsymbol{\eta}} \end{aligned} \quad (5)$$

where $\bar{\mathbf{H}} = \mathbf{H}_{\mathbf{W}}\mathbf{H}^{\mathrm{T}}\mathbf{H}$ and $\bar{\boldsymbol{\eta}} = \mathbf{H}_{\mathbf{W}}\mathbf{H}^{\mathrm{T}}\tilde{\boldsymbol{\eta}}$. It has been shown in [18] that, after the whitening filter, $\bar{\boldsymbol{\eta}}$ in (5) is a white noise, and $\bar{\mathbf{H}}$ in (5) has the same block diagonal structure as $\mathbf{H}^{\mathrm{T}}\mathbf{H}$. Hence the received symbols in $\bar{\mathbf{r}}$ can now be separated into G independent groups, and the ML decoding only need to jointly decode $2K/G$ real symbols. Hence *Theorem 1* is proved. ■

Theorem 2: For any two symbols that belong to different groups (indexed using subscripts q and p) in a QO-STBC to be orthogonal to each other, their dispersion matrices $\{\mathbf{A}_q, \mathbf{B}_q\}$ and $\{\mathbf{A}_p, \mathbf{B}_p\}$ must possess the following algebraic structure, herein referred to as *Quasi-Orthogonality Constraints* (QOC):

$$\begin{aligned} &\text{(i) } \mathbf{A}_q^{\mathrm{H}}\mathbf{A}_p = -\mathbf{A}_p^{\mathrm{H}}\mathbf{A}_q \\ &\text{(ii) } \mathbf{B}_q^{\mathrm{H}}\mathbf{B}_p = -\mathbf{B}_p^{\mathrm{H}}\mathbf{B}_q \qquad 1 \le q \notin \mathcal{G}(p) \le K \\ &\text{(iii) } \mathbf{A}_q^{\mathrm{H}}\mathbf{B}_p = \mathbf{B}_p^{\mathrm{H}}\mathbf{A}_q \end{aligned} \tag{6}$$

where $\mathcal{G}(p)$ represents a set of indexes of the symbols that are the in the same group as the symbol with index p, including p.

Proof of *Theorem 2*: The proof can be found in [9]. ■

Hence *Theorem 2* specifies the algebraic structure of a QO-STBC defined in *Definition 1*, whose ML decoding can be achieved by jointly decoding only a subset of the transmitted symbols, as proven by *Theorem 1*.

3.2. Maximal Symbolwise Diversity of a QO-STBC

The QOC in *Theorem 2* only specifies the decoupling of symbols during the decoding process of a QO-STBC; it does not guarantee good the decoding performance of the QO-STBC. To ensure that the designed QO-STBC can achieve full diversity, we first employ the maximal symbolwise diversity (MSD) [16,17] to add an additional constraint to the code structure, as shown below:

$$\mathbf{A}_q^{\mathrm{H}}\mathbf{A}_q = \mathbf{B}_q^{\mathrm{H}}\mathbf{B}_q = (T/K)\mathbf{I}_{N_t} \tag{7}$$

where the factor T / K is to normalize the total transmission power. By (7), we guarantee full diversity protection for the one-symbol error events, which has the smallest Euclidean distances [16,17]. To further protect against multiple-symbol error events so as to provide full diversity for all error events, CR can next be applied. This will be discussed in a later part of this paper.

4. FULL-RATE 4GP-QOSTBC

4.1. Code Construction

We propose a new class of QO-STBC that is always full-rate for any number of transmit antennas. In addition, this class of QO-STBC has the property of $G = 4$, such that by using linear processing, we can always separate the received symbols into four independent groups, for separate joint detection of $K / 4$ complex symbols each. This is half of the number of symbols required by joint detection for the QO-STBCs proposed in [3], [8] and [10].

Theorem 3: Given a 4Gp-QOSTBC for N_t transmit antennas, with code length T, and K sets of dispersion matrices denoted as $\{\underline{\mathbf{A}}_q, \underline{\mathbf{B}}_q\}$, $1 \le q \le K$. A 4Gp-QOSTBC with code length $2T$ for $2N_t$ transmit antennas, which consists of $2K$ sets of dispersion matrices denoted as $\{\mathbf{A}_q, \mathbf{B}_q\}$, $1 \le q \le 2K$, can be constructed using the following four mapping rules:

$$\begin{aligned} &\mathbf{A}_{2q-1} = \begin{bmatrix} \underline{\mathbf{A}}_q & \mathbf{0} \\ \mathbf{0} & \underline{\mathbf{A}}_q \end{bmatrix}; \ \mathbf{B}_{2q-1} = \begin{bmatrix} \mathbf{0} & j\underline{\mathbf{A}}_q \\ j\underline{\mathbf{A}}_q & \mathbf{0} \end{bmatrix}; \\ &\mathbf{A}_{2q} = \begin{bmatrix} j\underline{\mathbf{B}}_q & \mathbf{0} \\ \mathbf{0} & j\underline{\mathbf{B}}_q \end{bmatrix}; \quad \mathbf{B}_{2q} = \begin{bmatrix} \mathbf{0} & \underline{\mathbf{B}}_q \\ \underline{\mathbf{B}}_q & \mathbf{0} \end{bmatrix}. \end{aligned} \tag{8}$$

Proof of *Theorem 3*: This can be proved by showing that if the dispersion matrices $\{\underline{\mathbf{A}}_q, \underline{\mathbf{B}}_q\}$ satisfy the QOC with $\{\underline{\mathbf{A}}_p, \underline{\mathbf{B}}_p\}$ where $q \notin \mathcal{G}(p)$, then the dispersion matrices $\{\mathbf{A}_{2q-1}, \mathbf{B}_{2q-1}, \mathbf{A}_{2q}, \mathbf{B}_{2q}\}$ constructed from $\{\underline{\mathbf{A}}_q, \underline{\mathbf{B}}_q\}$ using (8) will satisfy QOC with $\{\mathbf{A}_{2p-1}, \mathbf{B}_{2p-1}, \mathbf{A}_{2p}, \mathbf{B}_{2p}\}$ constructed from $\{\underline{\mathbf{A}}_p, \underline{\mathbf{B}}_p\}$ using (8). The detailed proof is omitted here, as the steps are routine. ■

It should be noted that the code rate of the higher-order 4Gp-QOSTBC is $2K / 2T$ which is the same as the code rate of the lower-order 4Gp-QOSTBC, i.e. K / T, used to construct it. In addition, the constructed dispersion matrices always satisfy the MSD in (7) if the lower order dispersion matrices used to construct it satisfy MSD too.

The iterative construction of 4Gp-QOSTBC specified in (8) can start with the MDC-QOSTBC for four transmit antennas proposed in [13,14]. This is because MDC-QOSTBC is the smallest QO-STBC, which satisfying the definition of a 4Gp-QOSTBC. By using the four mapping rules in *Theorem 3*, we can obtain a 4Gp-QOSTBC for eight transmit antennas, which can be in turn be used to obtain a 4Gp-QOSTBC for sixteen transmit antennas, and so on. Since MDC-QOSTBC is full rate and satisfying MSD, the resultant 4Gp-QOSTBC constructed will also full rate and satisfy MSD as well. Furthermore, the constructed 4Gp-QOSTBCs are delay optimal, i.e. the code length is the same as the number of transmit antennas [10], if the number of transmit antennas is a power of two. This is because MDC-QOSTBC is a square design; hence all the 4Gp-QOSTBC constructed by *Theorem 3* will be square design as well.

Although the construction in *Theorem 3* is applicable for the case of number of transmit antennas is a power of two for delay-optimal codes. It has been shown in [13,14] that, by removing any number of codeword columns of a full-diversity QO-STBC, the resultant QO-STBC will support a smaller number of transmit antennas but remains full diversity with the same code rate and same number of groups (i.e. same ML decoding complexity).

4.2. Decoding Performance

We focus on 4Gp-QOSTBC for eight transmit antennas that is shown in (9)

$$\begin{bmatrix} c_1^R + jc_3^R & c_5^R + jc_7^R & -c_2^R + jc_4^R & -c_6^R + jc_8^R \\ -c_5^R + jc_7^R & c_1^R - jc_3^R & c_6^R + jc_8^R & -c_2^R - jc_4^R \\ -c_2^R + jc_4^R & -c_6^R + jc_8^R & c_1^R + jc_3^R & c_5^R + jc_7^R \\ c_6^R + jc_8^R & -c_2^R - jc_4^R & -c_5^R + jc_7^R & c_1^R - jc_3^R \\ -c_1^I - jc_3^I & -c_5^I - jc_7^I & -c_2^I + jc_4^I & -c_6^I + jc_8^I \\ c_5^I - jc_7^I & -c_1^I + jc_3^I & c_6^I + jc_8^I & -c_2^I - jc_4^I \\ -c_2^I + jc_4^I & -c_6^I + jc_8^I & -c_1^I - jc_3^I & -c_5^I - jc_7^I \\ c_6^I + jc_8^I & -c_2^I - jc_4^I & c_5^I - jc_7^I & -c_1^I + jc_3^I \end{bmatrix} \cdots \quad (9)$$

$$\cdots \begin{bmatrix} -c_1^I - jc_3^I & -c_5^I - jc_7^I & -c_2^I + jc_4^I & -c_6^I + jc_8^I \\ c_5^I - jc_7^I & -c_1^I + jc_3^I & c_6^I + jc_8^I & -c_2^I - jc_4^I \\ -c_2^I + jc_4^I & -c_6^I + jc_8^I & -c_1^I - jc_3^I & -c_5^I - jc_7^I \\ c_6^I + jc_8^I & -c_2^I - jc_4^I & c_5^I - jc_7^I & -c_1^I + jc_3^I \\ c_1^R + jc_3^R & c_5^R + jc_7^R & -c_2^R + jc_4^R & -c_6^R + jc_8^R \\ -c_5^R + jc_7^R & c_1^R - jc_3^R & c_6^R + jc_8^R & -c_2^R - jc_4^R \\ -c_2^R + jc_4^R & -c_6^R + jc_8^R & c_1^R + jc_3^R & c_5^R + jc_7^R \\ c_6^R + jc_8^R & -c_2^R - jc_4^R & -c_5^R + jc_7^R & c_1^R - jc_3^R \end{bmatrix}$$

To optimize the decoding performance of the code, we employ the constellation rotation technique [5-8]. For 4-QAM constellation, the optimum constellation rotation angle is found to be 7^0 for the symbols c_1, c_3, c_5 and c_7 and 23^0 for the symbols c_2, c_4, c_6 and c_8.

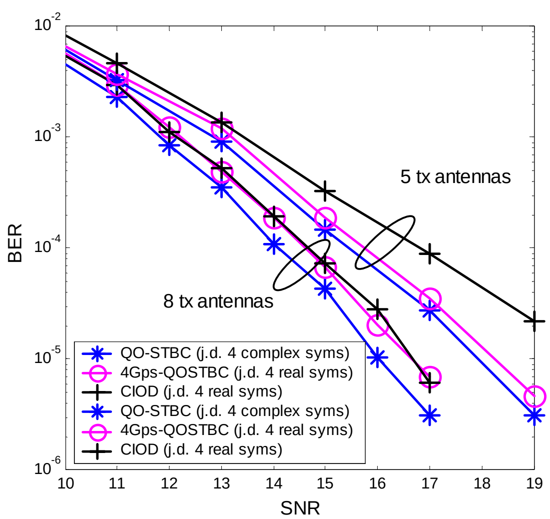

Figure 1 Simulated BER of full-rate STBCs with 4-QAM

The simulated bit error rate (BER) performances of full-rate 4Gp-QOSTBC for eight and five (the codeword five transmit antennas is obtained by removing the last three columns for eight transmit antennas) transmit antennas with 4-QAM constellation are shown in Figure 1. For the case of eight transmit antennas, 4Gp-QOSTBC is found to have approximately 0.5 dB loss in coding gain at a BER of 10^{-4} when compared with QO-STBC with two groups [5,8,10]. However the former only needs to jointly decode two real symbols, which is half the number of joint detection symbols required by the later. Furthermore, 4Gp-QOSTBC has the same decoding performance as CIOD (CIOD has been simulated by having the symbols 1, 3, 5, 7 rotated with 38^0; while symbols 2, 4, 6, 8 rotated with 23^0), but without the high peak-to-average power ratio problem as there is not any zero in the transmission matrix. For the case of five transmit antennas, the BER gap between 4Gp-QOSTBC and the existing QO-STBC with two groups is smaller, while the complexity advantage of the former remains. However, compared with CIOD, which has the same decoding complexity as 4Gp-QOSTBC, the latter gives a performance gain of 1.5dB at BER 10^{-5} and more subsequently.

Table 1 shows the decoding complexity and diversity product of the three STBCs for comparison. It can be seen that 4Gps-QOSTBC and CIOD have close diversity product at eight transmit antennas, while CIOD has a much lower diversity product than 4Gps-QOSTBC when five transmit antennas are used. These shown that our simulation results in Figure 1 are agreed with the theoretical coding gain calculation in Table 1. And QO-STBC with two groups [5,8,10] always has the maximum diversity product, but it has a higher decoding search space (joint detection (j.d.) of 8 real symbols) as compared with 4Gp-QOSTBC (j.d. of 4 real symbols).

Table 1 Diversity product of STBCs

STBC with CR	Number of real symbols for j.d.	Diversity product	
		5 tx antenna s	8 tx antennas
QO-STBC	8	0.2712	0.2187
4Gp-QOSTBC	4	0.2653	0.1727
CIOD	4	0.1790	0.1682

4.3. Extension to More Groups for Less Joint Detection Symbols

The four mapping rules proposed in *Theorem_3* can be extended to QO-STBC with more groups, such that the number of symbols required for joint detection is lesser, hence the ML decoding complexity is further reduced. For example, starting with the rate-3/4 MDC-QOSTBC for eight transmit antennas that is able to separate the symbols into 6 groups, we can construct a class of rate-3/4 6Gp-QOSTBC. Likewise can be said for rate-1/2 8Gp-QOSTBC, as shown in Table 2.

Furthermore, a tradeoff between the code rate and decoding complexity can be seen. For example the case of eight transmit antennas, we are able to achieve a code rate of 1 if we allow a joint detection of four real symbols, however if we only want to jointly decode two real symbols, then the code rate can achieved is only 3/4, this is further reduce to rate 1/2, if we only allow linear detection. It is interesting to note from Table 2 that, there is a relationship between the group size and code rate. When the size of groups is increase by 2 between the ranges from four to eight, there is a reduction of 1/4 in code rate. This is coincidentally matched with results in [19], where a rate 5/4 QO-STBC that can separate the symbols into 2 groups is found.

Table 2 Extension of 4Gp-QOSTBC

Gps	Rate	2 Tx	4 Tx	8 Tx	16 Tx
4	1	O-STBC j.d. = 1	MDC-QOSTBC j.d. = 2	4Gp-QOSTBC j.d. 4	4Gp-QOSTBC j.d. = 8
6	3/4	N.A.	O-STBC j.d. = 1	MDC-QOSTBC j.d. = 2	6Gp-QOSTBC j.d. = 4
8	1/2	N.A.	N.A.	O-STBC j.d. = 1	MDC-QOSTBC j.d. = 2

5. CONCLUSIONS

We design four mapping rules to construct a class of full-rate QO-STBC, denoted as 4Gp-QOSTBC, that can always separate the symbols into four independent groups by simply linear processing, such that ML decoding only need to jointly decode the symbols that are in the same group. Furthermore, such construction ensure maximal symbolwise diversity, hence the resultant 4Gp-QOSTBC can achieve full diversity after some form of constellation rotation. Simulation results show that the proposed full-rate 4Gp-QOSTBC has a comparable performance with existing full-rate QO-STBC but requires only half of the number of symbols required for joint detection during ML decoding. For example, our newly proposed 4Gp-QOSTBC only requires a joint detection of four real symbols for the case of eight transmit antennas as compared to four complex symbols for existing QO-STBC. Next we also discuss the extension of the proposed 4Gp-QOSTBC to 6Gp-QOSTBC and 8Gp-QOSTBC, it is interesting to find that when the group size is increase by two, there is a reduction of 1/4 in code rate.

6. REFERENCES

[1] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs", *IEEE Trans. on Information Theory,* vol. 45, pp. 1456-1467, Jul. 1999.

[2] H. Jafarkhani, "A quasi-orthogonal space-time block code", *IEEE Trans. on Communications,* vol. 49, pp. 1-4, Jan. 2001.

[3] O. Tirkkonen, A. Boariu, and A. Hottinen, "Minimal non-orthogonality rate 1 space-time block code for 3+ tx antennas", *IEEE ISSSTA 2000,* vol. 2, pp. 429-432.

[4] C. B. Papadias and G. J. Foschini, "Capacity-approaching space-time codes for systems employing four transmitter antennas", *IEEE Trans. on Information Theory*, vol. 49, pp. 726- 733, Mar. 2003.

[5] O. Tirkkonen, "Optimizing space-time block codes by constellation rotations", *Finnish Wireless Communications Workshop 2001,* pp. 59-60.

[6] N. Sharma and C. B. Papadias, "Improved quasi-orthogonal codes through constellation rotation", *IEEE Trans. on Communications*, vol. 51, pp. 332- 335, Mar. 2003.

[7] W. Su and X. Xia, "Quasi-orthogonal space-time block codes with full diversity", *IEEE Globecom 2002,* vol. 2, pp. 1098 –1102.

[8] C. Yuen, Y. L. Guan, T. T. Tjhung, "Full-Rate Full-Diversity STBC with Constellation Rotation". *IEEE VTC 2003-Spring, Vol.1*, Page(s): 296 –300.

[9] C. Yuen, Y. L. Guan, and T. T. Tjhung, "Improved quasi-orthogonal STBC with group-constrained linear transformation", *IEEE Globecom 2004*, pp. 550 - 554.

[10] N. Sharma and C. B. Papadias, "Full Rate Full Diversity Linear Quasi-Orthogonal Space-Time Codes For Any Transmit Antennas", *EURASIP Journal on Applied Signal Processing*.

[11] B. S. Rajan, M. H. Lee, and Z. A. Khan, "A Rate-One Full-Diversity Quasi-Orthogonal Design for Eight Tx Antennas", *Internal Report TR-PME-2002-15*, available at: http://pal.ece.iisc.ernet.in/PAM/tech_rep02.html.

[12] Z. A. Khan, B. S. Rajan, and M. H. Lee, "On Single-Symbol and Double-Symbol Decodable STBCs", *ISIT 2003*, pp. 127.

[13] C. Yuen, Y. L. Guan, and T. T. Tjhung, "Construction of Quasi-Orthogonal STBC with Minimum Decoding Complexity". *IEEE ISIT 2004*, pp. 309. Also accepted for publication in *IEEE Trans. Wireless Comms*.

[14] C. Yuen, Y. L. Guan, and T. T. Tjhung, "Quasi-orthogonal STBC with minimum decoding complexity: further results", *IEEE WCNC 2005*, pp. 483 - 488.

[15] A. Hottinen, K. Kuchi, and O. Tirkkonen, "A Space-time Coding Concept For A Multi-Element Transmitter", *Canadian Workshop in IT 2001*.

[16] B. Hassibi and B. M. Hochwald, "High-rate codes that are linear in space and time", *IEEE Trans. on Information Theory*, vol. 48, pp. 1804 –1824, Jul. 2002.

[17] A. Hottinen, O. Tirkkonen, and R. Wichman, *Multi-antenna Transceiver Techniques for 3G and Beyond*, John Wiley & Sons, 2003.

[18] C. Yuen, Y. L. Guan, and T. T. Tjhung, "Decoding of quasi-orthogonal space-time block code with noise whitening", *IEEE PIMRC 2003*, pp. 2166-2170.

[19] C. Yuen, Y. L. Guan, and T. T. Tjhung, "On search of high-rate quasi-orthogonal space-time block code", *IEEE PIMRC 2004*, pp. 1647 - 1651.