Transmit antenna shuffling for quasi-orthogonal space-time block codes with linear receivers

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***Abstract*— In this letter, we propose a transmit antenna shuffling scheme for quasi-orthogonal space-time block codes (QO-STBCs). We show that by adaptively mapping the space-time sequences of the QO-STBC to the appropriate transmit antennas depending on the channel condition, the proposed scheme can improve its transmit diversity with limited feedback information. The performance of the scheme with various numbers of shuffling patterns is analyzed. The bit error probability of the schemes is evaluated by simulations. It is demonstrated that with the linear zero-forcing (ZF) and the minimum mean squared error (MMSE) receivers, the closed-loop QO-STBC using two feedback bits can achieve almost the same performance as the ideal 4-path diversity and it is about 4-5 dB better than the open loop schemes.**

***Index Terms*— QO-STBCs, antenna shuffling, linear receivers.**

I. Introduction

OVER the past few years, multiple-input and multiple-output (MIMO) systems were demonstrated to provide a potential capacity gain compared to single-antenna communication systems [1]. In order to approach the capacity of MIMO systems, space-time coding (STC) has received the significant amount of attention. In [2], Alamouti introduced a very simple scheme which allows the transmission from two transmit antennas with the same data rate as on a single antenna but increasing the diversity at the receiver from one to two in flat fading channels. However, it is demonstrated that the complex orthogonal full rate design, offering full diversity, was limited to the case of two transmit antennas. When three or four transmit antennas were considered, the maximum symbol transmission rate of the complex orthogonal STBCs with the linear processing was 3/4 [3]. Due to this drawback, various quasi-orthogonal STBCs (QO-STBCs) have been proposed to achieve a full rate (R=1) for more than 2 transmit antennas at the expense of loosing the diversity gain and increasing the decoding complexity [4]-[6].

Recently, a lot of researches have been put into designing the STBCs with full rate and full diversity for four transmit antennas [7]-[9]. For open-loop communication systems, the optimum constellation rotation proposed for QO-STBCs with different modulation schemes is the one of good diversity improvement approaches [7]. For closed-loop communication systems, Milleth *et al.* has proposed a quantized phase-only feedback method for QO-STBCs in [8]. The technique that we present here has a slightly higher computational complexity than [9]. While [9] used orthogonal Alamouti blocks to build the larger STBCs, here, we have an alternative approach by starting with the quasi-orthogonal design of [4].

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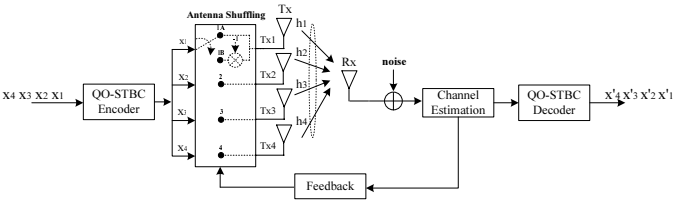

Fig. 1. The baseband representation of the proposed closed-loop system.

In this letter, a transmit antenna shuffling (TAS) scheme is proposed for various QO-STBCs using four transmit antennas. The optimum antenna shuffling pattern can be selected to improve the transmit diversity with limited feedback information during the whole signal transmission. Linear receivers such as zero-forcing (ZF) receivers and minimum mean squared error (MMSE) receivers are adopted for the proposed closed-loop QO-STBC. The bit error ratio (BER) performance is evaluated for our scheme.

II. The QO-STBC for Four Transmit Antennas

In this section, Jafarkhani's QO-STBC with four transmit antennas is described in order to facilitate the introduction of the new scheme. The (4×4) QO-STBC is given by

$$C_J = \begin{bmatrix} A_{12} & A_{34} \\ -A_{34}^* & A_{12}^* \end{bmatrix} \tag{1}$$

where A_{12} and A_{34} are the two (2×2) building blocks based on the Alamouti scheme of two transmit antennas,

$$A_{12} = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \quad and \quad A_{34} = \begin{bmatrix} x_3 & x_4 \\ -x_4^* & x_3^* \end{bmatrix}. \tag{2}$$

When one receive antenna is used, the received signals during four successive time slots can be expressed as

$$\underbrace{\begin{bmatrix} r_1 \\ r_2^* \\ r_3^* \\ r_4 \end{bmatrix}}_{R} = \underbrace{\begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_2^* & -h_1^* & h_4^* & -h_3^* \\ h_3^* & h_4^* & -h_1^* & -h_2^* \\ h_4 & -h_3 & -h_2 & h_1 \end{bmatrix}}_{H_J} \cdot \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}}_{X} + \underbrace{\begin{bmatrix} n_1 \\ n_2^* \\ n_3^* \\ n_4 \end{bmatrix}}_{\widetilde{N}} \tag{3}$$

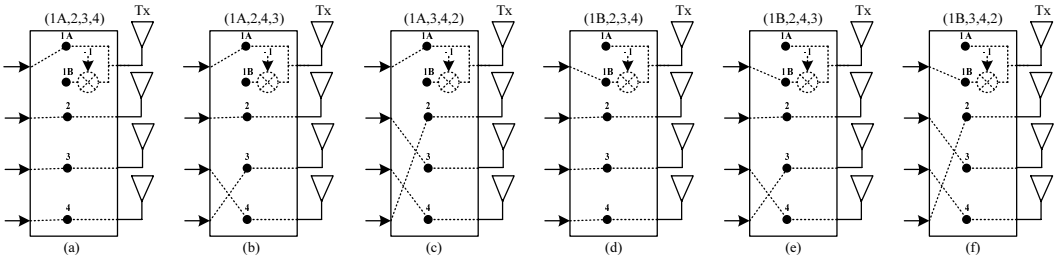

Fig. 2. Six antenna shuffling patterns for Jafarkhani's QO-STBC.

where the channel coefficients h_1, h_2, h_3 and h_4, are modeled as independent zero mean complex Gaussian random variables with variance 0.5 per real dimension. Applying the matched filtering at the receiver with H_J^H matrix, we obtain a Grammian matrix

$$G_J = H_J^H H_J = \underbrace{h^2 \begin{bmatrix} I_2 & 0 \\ 0 & I_2 \end{bmatrix}}_{D_J} + \underbrace{h^2 \begin{bmatrix} 0 & WJ_2 \\ -WJ_2 & 0 \end{bmatrix}}_{V_J} \tag{4}$$

where $h^2 = \sum_{i=1}^{4} |h_i|^2$ indicates the total channel gain for the four transmit antennas, W can be interpreted as the channel dependent interference parameter, given by $W = 2Re(h_1 h_4^* - h_2 h_3^*)/h^2$, I_2 is a two-dimensional identical matrix and J_2 is a matrix given by

$$J_2 = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}. \tag{5}$$

As presented in (4), the Grammian matrix, G_J, can be divided into two components, which are the channel gain matrix, D_J, and the interference matrix, V_J,

$$G_J = D_J + V_J. \tag{6}$$

It is well known that the presence of the channel dependent interference, W, in V_J can cause the performance degradation in contrast with the optimal orthogonal design. Therefore, in order to achieve the ideal 4-path diversity, G_J should approach D_J as close as possible, which means the absolute value of W in V_J should be as small as possible. The effect of W in V_J is explained in [6]. To improve the transmit diversity, we present an efficient antenna shuffling scheme for QO-STBCs to alleviate the interference by using two feedback bits.

III. The Proposed TAS scheme for the QO-STBC

The block diagram of the proposed closed-loop QO-STBC with four transmit antennas and one receive antenna is depicted in Fig. 1. We assume that the channel state information (CSI) can be estimated at the receiver. Considering that the channel interference parameter, W, strongly depends on the equivalent channel matrix, H_J, we can implement an antenna shuffling structure between the QO-STBC encoder and four transmit antennas to minimize the channel interference term V_J in (6). This is achieved by adaptively mapping the space-time sequences from the QO-STBC encoder to the appropriate transmit antennas depending on the channel condition such that the channel interference parameter W is minimized.

In Fig. 2, we show six different antenna shuffling patterns for Jafarkhani's QO-STBC. For example, the pattern in Fig. 2 (b) is denoted by $(1A, 2, 4, 3)$, which means the four rows of the QO-STBC will be transmitted from antenna 1, 2, 4, and 3, respectively. The pattern in Fig. 2 (f) is $(1B, 3, 4, 2)$ representing that the four rows of the QO-STBC are transmitted from antenna 1, 3, 4, and 2, respectively. However, signals for the antenna 1 have a 180°-phase shift before transmission. For these six cases, we can obtain the values of W as

$$\begin{aligned} W_1 &= \frac{2Re(h_1 h_4^* - h_2 h_3^*)}{h^2}, \; W_2 = \frac{2Re(h_1 h_3^* - h_2 h_4^*)}{h^2}, \\ W_3 &= \frac{2Re(h_1 h_2^* - h_3 h_4^*)}{h^2}, \; W_4 = \frac{-2Re(h_1 h_4^* + h_2 h_3^*)}{h^2}, \\ W_5 &= \frac{-2Re(h_1 h_3^* + h_2 h_4^*)}{h^2}, \; W_6 = \frac{-2Re(h_1 h_2^* + h_3 h_4^*)}{h^2}, \end{aligned} \tag{7}$$

where $h^2 = |h_1|^2 + |h_2|^2 + |h_3|^2 + |h_4|^2$.

In order to achieve the optimum performance, the QO-STBC selects an antenna shuffling pattern to minimize $|W|$. Now we analyze how the antenna shuffling can reduce the channel interference. Since the interference parameter W is a random variable, we here consider the statistic average of the interference variable W for using various numbers of shuffling patterns, n, where $n \in [1, 6]$. It is obvious that choosing $n = 1$ means we always use a fixed antenna mapping pattern, or there is no antenna shuffling, and choosing $n = 6$ means that we can use all six antenna shuffling patterns. Let us denote the statistic average of the interference variable W by $E[|W_s^n|]$ with n shuffling patterns. We have

$$E(|W_s^n|) = \int_0^1 n[1 - F_W(w)]^{n-1} f_W(w) w dw \tag{8}$$

where $f_W(w)$ is the probability density function (PDF) of W, and $F_W(w)$ is the accumulative density function (CDF) of W. The $f_W(w)$ is given by [6]

$$f_W(w) = \frac{3}{2}(1 - w^2). \tag{9}$$

Substituting (9) into (8), we obtain the average interference for various shuffling patterns n. The results are shown in Table I.

TABLE I

The average interference for various shuffling patterns n

n	1	2	3	4	5	6
$E[\|W_s^n\|]$	0.375	0.235	0.173	0.136	0.113	0.096

From Table I, we see that with $n = 4$ antenna shuffling patterns, the average interference W can be reduced by 64% relative to the case without antenna shuffling $n = 1$. Further

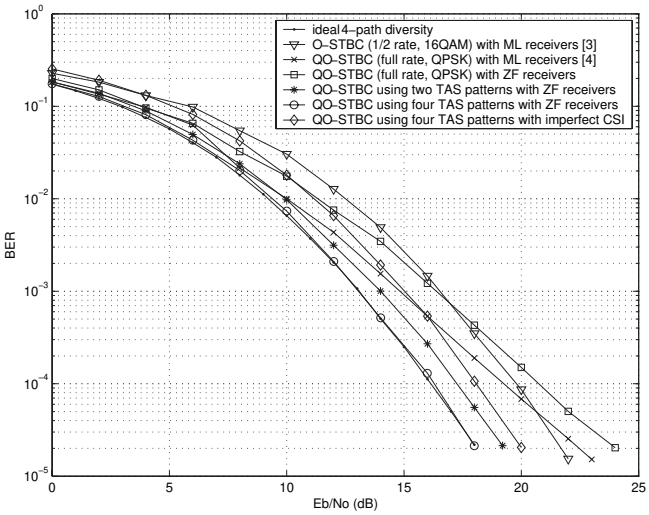

Fig. 3. TAS scheme for the (4×4) QO-STBC with ZF receivers.

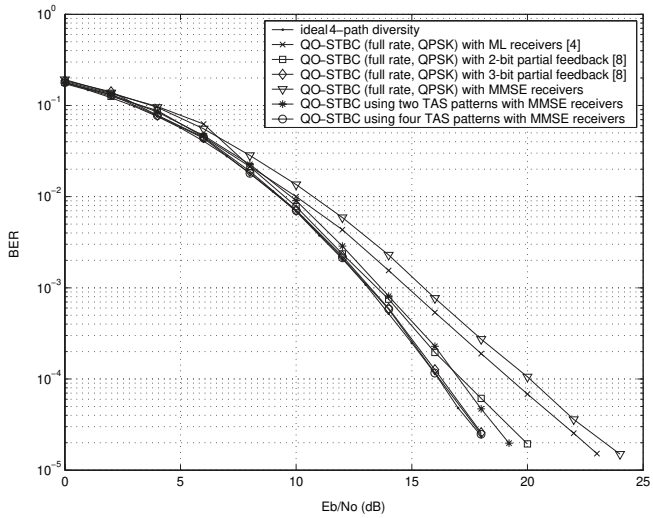

Fig. 4. TAS scheme for the (4×4) QO-STBC with MMSE receivers.

increasing the shuffling patterns from four to six can reduce the interference by another 10.4%. However, this requires 3-bit feedback rather than 2-bit feedback during each channel coherence time interval. For practical reasons, here we consider 2-bit feedback scheme with four antenna shuffling patterns. It is well known that the QO-STBC using different patterns have similar performance because the same code matrix is used during the whole signal transmission. Therefore, arbitrary four antenna shuffling patterns can be used. For the convenience, we can employ the first four patterns in Fig. 2, $(1A, 2, 3, 4)$, $(1A, 2, 4, 3)$, $(1A, 3, 4, 2)$ and $(1B, 2, 3, 4)$ in this letter. In general, for four transmit antennas, we always find six shuffling patterns with different $|W|$ for any QO-STBCs.

IV. Simulation Results

In this section, we evaluate the error performance of the proposed scheme in uncorrelated quasi-static flat fading channels. For the closed-loop system with four transmit antennas and one receive antenna, we have simulated the BER against E_b/N_o using QPSK symbols leading to an information rate of 2 bits/sec/Hz. Each frame consists of 2000 symbols in our simulation. In Fig. 3, we show the performance of the proposed closed-loop QO-STBC with ZF receivers. The proposed QO-STBC using four antenna shuffling patterns can achieve almost the same diversity order as the O-STBC [3]. This is evident from the slope of curves in the high E_b/N_o region. As shown in Fig. 3, at the BER is 10^{-4}, the proposed scheme with 2-bit feedback can get 1.5 dB and 5 dB over that with 1 bit feedback and the QO-STBC[4] with ZF receivers, respectively. Furthermore, the system performance with the imperfect CSI is investigated. A pilot sequence with a length of 8 symbols is inserted at the beginning of each frame for the channel estimation. The simulation results show that due to imperfect channel estimation, the performance of the closed-loop QO-STBC using four TAS patterns is degraded by about 1.8 dB compared to the case with the ideal CSI at the BER of 10^{-4}.

Fig. 4 shows the simulation results for the QO-STBC with MMSE receivers. At the BER of 10^{-4}, the code using four TAS patterns gets about 4 dB gain over the QO-STBC [4] with MMSE receivers. We further compare our results with the scheme described in [8]. Simulations show that at the BER is 10^{-5}, the QO-STBC using four TAS patterns gets about 2.1 dB over that with 2-bit feedback [8]. It is worth pointing out that our scheme has a lower complexity since it requires less bits to achieve the ideal 4-path diversity than the design in [8].

V. Conclusion

In this letter, we propose a closed-loop QO-STBC with TAS. ZF receivers and MMSE receivers are adopted in this system to obtain a lower decoding complexity. It is demonstrated that the QO-STBC with four antenna shuffling patterns can achieve almost the same performance of the ideal 4-path diversity. In particular, the proposed TAS scheme can be designed for any QO-STBCs to enhance the performance with a limited amount of feedback information.

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