An Efficient Space Time Block Code for LTE-A System

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***Abstract*—In this study, a new space time block code (STBC) is proposed for long term evolution-advanced (LTE-A) system that is equipped with three time slots and two antennas. The introduced STBC has the following characteristics: i) it achieves rate one and full diversity, ii) its maximum likelihood (ML) decoding requires a joint detection of three real symbols, iii) the minimum determinant value (MDV) does not vanish by increasing signal constellation size, and iv) bit error rate (BER) results show that the proposed STBC outperforms previously presented schemes for LTE-A at high SNRs.**

***Index Terms*—LTE-A, maximum likelihood detection, minimum determinant, space time block code (STBC).**

I. Introduction

MULTIPLE input multiple output (MIMO) systems have received great attention due to achieving higher data rates and higher performance than the traditional single antenna systems in wireless communications. Space time block codes (STBCs) are known as well-suited techniques that provide an effective diversity method to mitigate fading in wireless channels. Design of the codes that achieve full rate and full diversity [1] is of great interest.

The third generation partnership project (3GPP) has been working on the next generation wireless systems (4G) under the project long term evolution-advanced (LTE-A) [2]. The number of time slots in 3GPP for data transmission is not guaranteed to be an even number. In the LTE-A, the mobile station is equipped with two antennas where its frame structure allows three time slots for data transmission [3]. Therefore, STBC is an efficient scheme to combat channel fading between the mobile station and base station in LTE-A system.

Hybrid STBC (AL code) [4] is the first STBC proposed for three time slots and two antennas. Its encoding matrix uses two time slot Alamouti [5] scheme followed by one time slot repetition transmission. The hybrid scheme in [4] has rate one and its decoding is linear, but it does not achieve full diversity. Quasi orthogonal STBC (QSTBC) proposed in [6], is another scheme that achieves full diversity and rate one with the maximum likelihood (ML) detection complexity of order $\mathrm{O}(M^2)$, where M is the size of the used symbol constellation. The minimum determinant value (MDV) of this code vanishes by increasing M. A version of group decodable STBC (GSTBC) scheme was introduced in [7] for LTE-A system that achieves rate one and full diversity with symbol-wise detection complexity of order $\mathrm{O}(M^1)$. Recently, a novel STBC scheme has been proposed in [8] which achieves rate one and full diversity and has non-vanishing determinant characteristic. It has detection complexity of order $\mathrm{O}(M^{1.5})$, and its bit error rate (BER) performance is close to [7].

In this study, we present an efficient STBC for LTE-A system. The proposed scheme has interesting characteristics as: i) it achieves rate one and full diversity, ii) its ML decoding needs a joint detection of three real symbols, iii) the MDV does not vanish by increasing signal constellation size, iv) it gives good trace criterion [9], [10] in terms of orthogonality of columns of encoding matrix and high minimum trace value [9], [10], v) it has high MDV, and vi) it achieves lower BER than [7] at high SNRs and outperforms [6] and [8] in all SNRs.

Notation: Throughout the letter, $j = \sqrt{-1}$, small letters, bold letters, and bold capital letters denote scalars, vectors, and matrices, respectively. $\mathbf{A}^H$ represents the conjugate transpose of matrix $\mathbf{A}$. $(\cdot)^R, (\cdot)^I, (\cdot)^*$, $E[\cdot]$, and $|\cdot|$ indicate the real part, imaginary part, complex conjugate, expectation, and absolute value, respectively. The quantity $\mathbf{X}$ denotes the STBC encoding matrix.

II. System Model

We consider a MIMO system with N_t transmit antennas and N_r receive antennas. It is assumed that the channel is quasi-static Rayleigh flat fading and constant in the block length of T. We also assume that the channel state information (CSI) is known at the receiver but unknown at the transmitter. The received signal can be expressed as

$$\mathbf{Y} = \sqrt{q}\mathbf{X}\mathbf{H} + \mathbf{Z} \tag{1}$$

where $\mathbf{Y}$ is the $T \times N_r$ complex matrix of the received signals and $\mathbf{X}$ is $T \times N_t$ complex matrix of the transmitted symbols that are drawn from an M-size constellation. The normalization q is to ensure that the SNR at the receiver is independent from the number of transmit antennas and depends on the throughput. $\mathbf{H}$ is the $N_t \times N_r$ complex matrix that contains channel coefficients having Gaussian distribution with zero mean and unit variance. $\mathbf{Z}$ is $T \times N_r$ complex noise matrix whose elements are i.i.d. complex Gaussian random variables with zero mean and unit variance.

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III. Proposed STBC

In this section, we propose a rate one and full diversity code for LTE-A system ($T = 3$ and $N_t = 2$). The motivation is to design a code in which each symbol appears in four entries of the encoding matrix (more than [8]) in a way that it yields better coding gain and trace criteria. Moreover, our goal is to find a code that uses equal number of symbols in all entries of encoding matrix as opposed to previously presented codes in [6], [7], and [8]. By this manner, the interferences within each entry of the encoding matrix will be the same. In addition, we aim to design a code with low detection complexity. We also use the symbols and their conjugates such that the columns of encoding code matrix are orthogonal. Orthogonality satisfies an important part of trace criterion [9], [10].

According to the trace criterion [9] and [10], the best suboptimal codes are those for which the matrix $\bar{\mathbf{X}}^H\bar{\mathbf{X}}, (\bar{\mathbf{X}} = \mathbf{X} - \hat{\mathbf{X}}, \mathbf{X} \neq \hat{\mathbf{X}})$ where $\mathbf{X}$ is the transmitted block code and $\hat{\mathbf{X}}$ is the detected one, are such that the main diagonal elements are as close as possible to each other, and the row-wise sum of the absolute values of the elements of off main diagonal is as small as possible for each row.

The places of each symbol in the encoding matrix should be selected such that better trace criterion and high minimum determinant value are obtained. To achieve high trace value, we place symbols in the encoding matrix in a manner that in addition to orthogonality of columns of encoding matrix, the cross terms in $trace(\bar{\mathbf{X}}^H\bar{\mathbf{X}})$ cancel each other and the square terms are added. This also leads to low detection complexity.

Considering the mentioned conditions, our designed code is obtained as follows

$$\mathbf{X}_p = \frac{1}{\sqrt{2}}\begin{bmatrix} x_1 - x_2 & x_1^* + x_2^* \\ x_2 + x_3 & x_2^* - x_3^* \\ x_3 - x_1 & x_3^* + x_1^* \end{bmatrix} \tag{2}$$

Therefore,

$$\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p = \begin{bmatrix} L_1 & 0 \\ 0 & L_2 \end{bmatrix} \tag{3}$$

where

$$L_1 = 0.5\left(|\bar{x}_1 - \bar{x}_2|^2 + |\bar{x}_2 + \bar{x}_3|^2 + |\bar{x}_3 - \bar{x}_1|^2\right) \tag{4}$$
$$L_2 = 0.5\left(|\bar{x}_1 + \bar{x}_2|^2 + |\bar{x}_2 - \bar{x}_3|^2 + |\bar{x}_3 + \bar{x}_1|^2\right) \tag{5}$$

where $\bar{x}_i = x_i - \hat{x}_i$, x_i is the transmitted symbol and $\hat{x}_i$ is the detected symbol. Considering (3)-(5), we observe that $\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p$ matrix of the proposed scheme is diagonal with unequal main diagonal elements. It is also seen from (2) that the columns of the code are orthogonal. In addition, since each entry of the proposed code matrix contains two symbols, the intersymbol interference is the same for all entries.

The trace of the proposed code is calculated as

$$trace\left(\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p\right) = L_1 + L_2 = 2\left(|\bar{x}_1|^2 + |\bar{x}_2|^2 + |\bar{x}_3|^2\right) \tag{6}$$

It is observed that the trace contains only square terms. The determinant of $\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p$ is computed as

$$\begin{aligned}\det\left(\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p\right) = L_1L_2 = 0.25&\left[(\bar{s}_1 - \bar{s}_3)^2 + (\bar{s}_3 + \bar{s}_5)^2 + (\bar{s}_5 - \bar{s}_1)^2\right.\\ &\left.+ (\bar{s}_2 - \bar{s}_4)^2 + (\bar{s}_4 + \bar{s}_6)^2 + (\bar{s}_6 - \bar{s}_2)^2\right]\\ &\times\left[(\bar{s}_1 + \bar{s}_3)^2 + (\bar{s}_3 - \bar{s}_5)^2 + (\bar{s}_5 + \bar{s}_1)^2\right.\\ &\left.+ (\bar{s}_2 + \bar{s}_4)^2 + (\bar{s}_4 - \bar{s}_6)^2 + (\bar{s}_6 + \bar{s}_2)^2\right]\end{aligned} \tag{7}$$

where

$$x_1 = s_1 + js_2, x_2 = s_3 + js_4, x_3 = s_5 + js_6 \tag{8}$$

and $\bar{s}_i = s_i - \hat{s}_i$ where s_i is the real or imaginary part of the transmitted symbol and $\hat{s}_i$ is the corresponding detected part. It is clear that the determinant is nonnegative. But for example if $\bar{s}_1 = \bar{s}_3 = \bar{s}_5 = 0$ and $\bar{s}_2 = -\bar{s}_4 = -\bar{s}_6$, then $\det(\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p) = 0$. Therefore, in this case the proposed code cannot achieve full diversity. To escape zero determinant, we avoid canceling the terms in the parenthesis (for example $(\bar{s}_1 - \bar{s}_3)$). To this end, we use stretching technique [11] as

$$x_1 = s_1 + js_2 \tag{9}$$
$$x_2 = as_3 + j\sqrt{2 - a^2}s_4 \tag{10}$$
$$x_3 = \sqrt{2 - b^2}s_5 + jbs_6 \tag{11}$$

which guarantees $E[|x_i|^2]$ remains unchanged after stretching, $0 < a, b < \sqrt{2}$, and $a, b \neq 1$. In this way, full diversity is achieved. In order to obtain the optimum coding gain, it is desired to maximize the minimum of $\det(\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p)$. The optimization of encoding matrix has been considered in [11] and [12].

A. Non-Vanishing Property

Here, we prove that the MDV does not vanish by increasing symbol constellation size. For standard M-QAM, we consider $\bar{s}_i = d_{\min}m_i$ where m_i is an integer number and $d_{\min}$ is the minimum Euclidian distance between the symbols in the constellation. We assume $d_{\min} = 2$ in the trace and determinant evaluation of different codes.

Considering (7), after stretching, we obtain $\det(\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p) = 0.25d_{\min}^4L_1'L_2'$ where

$$\begin{aligned}L_1' = &(m_1 - am_3)^2 + (am_3 + \sqrt{2 - b^2}m_5)^2\\ &+ (\sqrt{2 - b^2}m_5 - m_1)^2 + (m_2 - \sqrt{2 - a^2}m_4)^2\\ &+ (\sqrt{2 - a^2}m_4 + bm_6)^2 + (bm_6 - m_2)^2\end{aligned} \tag{12}$$
$$\begin{aligned}L_2' = &(m_1 + am_3)^2 + (am_3 - \sqrt{2 - b^2}m_5)^2\\ &+ (\sqrt{2 - b^2}m_5 + m_1)^2 + (m_2 + \sqrt{2 - a^2}m_4)^2\\ &+ (\sqrt{2 - a^2}m_4 - bm_6)^2 + (bm_6 + m_2)^2\end{aligned} \tag{13}$$

From the above, we observe that

$$\begin{aligned}L_1'L_2' = &\left(g_1\left(m_1, m_3, m_5\right) + g_2\left(m_2, m_4, m_6\right)\right)\\ &\cdot\left(g_3\left(m_1, m_3, m_5\right) + g_4\left(m_2, m_4, m_6\right)\right)\end{aligned} \tag{14}$$

where g_is are nonnegative functions and g_1 and g_3 are independent of g_2 and g_4. It can be found that the minimum of $L_1'L_2'$ is obtained in the two cases: 1) $m_2 = m_4 = m_6 = 0$, 2) $m_1 = m_3 = m_5 = 0$. The other cases result in higher values. Below, we assess the two cases.

Case 1) $m_2 = m_4 = m_6 = 0$, then $g_2 = g_4 = 0$ and

$$\begin{aligned}L_1' = &(m_1 - am_3)^2 + (am_3 + \sqrt{2 - b^2}m_5)^2\\ &+ (\sqrt{2 - b^2}m_5 - m_1)^2\end{aligned} \tag{15}$$
$$\begin{aligned}L_2' = &(m_1 + am_3)^2 + (am_3 - \sqrt{2 - b^2}m_5)^2\\ &+ (\sqrt{2 - b^2}m_5 + m_1)^2\end{aligned} \tag{16}$$

In this case, we consider two options (i and ii).

i) One of the m_1, m_3, or m_5 is zero.

— If $m_1 = 0$, then

$$L_1' L_2' = 4a^4 {m_3}^4 + 4\left(2-b^2\right)^2 {m_5}^4 + 4a^2\left(2-b^2\right){m_3}^2{m_5}^2 \quad (17)$$

The minimum of $L_1'L_2'$ is obtained for $|m_3| = 1, m_5 = 0$ or $m_3 = 0, |m_5| = 1$ which result in $\min_1 = 4a^4$ or $\min_2 = 4(2-b^2)^2$, respectively.

— If $m_3 = 0$, similar to the above discussion, we have $\min_3 = 4$ or $\min_4 = 4(2-b^2)^2$.

— If $m_5 = 0$, we obtain $\min_5 = 4a^4$ or $\min_6 = 4$.

ii) None of m_1, m_3, and m_5 are zero. It can be found that

— L_2' is minimum if $m_3m_1 < 0, m_3m_5 > 0$, and $m_1m_5 < 0$, which is possible.

— L_1' is minimum if $m_3m_1 > 0, m_3m_5 < 0$, and $m_1m_5 > 0$ which is not possible.

We can conclude that $\min(L_1') > \min(L_2')$. Thus, to minimize $L_1'L_2'$ we minimize L_2' and $L_1{}' + L_2{}'$ simultaneously which is possible. From (15) and (16), we have

$$L_1' + L_2' = 4\left({m_1}^2 + a^2{m_3}^2 + \left(2-b^2\right){m_5}^2\right) \quad (18)$$

If $m_1 = -m_3 = -m_5 = \pm 1$, then $L_1' + L_2'$ and $\min\{L_1', L_2'\}$ are minimized simultaneously which give $\min(L_1'L_2')$ as

$$\begin{aligned}\min{}_7 = 4&\left(1 + a^2 + \left(2-b^2\right) + a + a\sqrt{2-b^2} + \sqrt{2-b^2}\right)\\ &\cdot\left(1 + a^2 + \left(2-b^2\right) - a - a\sqrt{2-b^2} - \sqrt{2-b^2}\right)\end{aligned}$$

Case 2) $m_1 = m_3 = m_5 = 0$, similar to the case 1 discussions, we obtain the following minimums.

$$\begin{aligned}&\min{}_8 = 4b^4, \min{}_9 = 4\left(2-a^2\right)^2, \min{}_{10} = 4,\\ &\min{}_{11} = 4\left(2-a^2\right)^2, \min{}_{12} = 4b^4, \min{}_{13} = 4,\\ &\min{}_{14} = 4\left(1 + b^2 + \left(2-a^2\right) + b + b\sqrt{2-a^2} + \sqrt{2-a^2}\right)\\ &\qquad\times\left(1 + b^2 + \left(2-a^2\right) - b - b\sqrt{2-a^2} - \sqrt{2-a^2}\right)\end{aligned}$$

Considering the minimums of case 1 and case 2, we observe that they are obtained when $m_i \in \{0, \pm 1\}$, which means the minimum distance of constellation determines the minimums. Therefore, by increasing the constellation size, the minimum values do not decrease; hence the proposed code has the non-vanishing property.

B. Maximization of MDV

Now, we obtain the optimum values of a and b that maximize the MDV, i.e., achieve the maximum coding gain.

$$\begin{aligned}a^*, b^* &= \arg\max_{a,b}\{\min\{\min{}_1, \min{}_2, \ldots, \min{}_{14}\}\}\\ &= \arg\max_{a,b}\left\{\min\left[4a^4, 4b^4, 4\left(2-a^2\right)^2, 4\left(2-b^2\right)^2,\right.\right.\\ &\qquad \left.\left.\min{}_7, \min{}_{14}\right]\right\} \quad (19)\end{aligned}$$

After manipulation, we obtain $a^* = 0.8245$ and $b^* = 0.8245$ which yield $\mathrm{MDV} = 0.25d_{\min}^4 \times 1.8485 = 7.39$.

By imposing the coefficients a and b, the trace after stretching will be as

$$\begin{aligned}trace\left(\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p\right) &= 2\bar{s}_1^2 + 2\bar{s}_2^2 + 2a^2\bar{s}_3^2 + 2\left(2-a^2\right)\bar{s}_4^2\\ &+ 2\left(2-b^2\right)\bar{s}_5^2 + 2b^2\bar{s}_6^2 \quad (20)\end{aligned}$$

The maximum value of minimum trace is obtained as 8 when $a = 1$ and $b = 1$ (no stretching). But in this case, full diversity is lost as mentioned. For $a^* = 0.8245$ and $b^* = 0.8245$, we have

$$\min\left[trace(\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p)\right] = 1.36d_{\min}^2 = 5.44. \quad (21)$$

C. Detection Complexity

Consider a single antenna receiver, the ML decoder metric for the proposed code can be obtained as

$$\|\mathbf{Y} - \mathbf{X}_p\mathbf{h}\|^2 \equiv f_R(s_1, s_3, s_5) + f_I(s_2, s_4, s_6) \quad (22)$$

where

$$\begin{aligned}f_R(s_1,s_3,s_5) = &-\sqrt{2}\mathrm{Re}\left\{r_3\left(h_1^*\left(\sqrt{2-b^2}s_5 - s_1\right)\right.\right.\\ &\left.\left.+ h_2^*\left(\sqrt{2-b^2}s_5 + s_1\right)\right)\right\}\\ &-\sqrt{2}\mathrm{Re}\left\{r_2\left(h_1^*\left(as_3 + \sqrt{2-b^2}s_5\right)\right.\right.\\ &\left.\left.+ h_2^*\left(as_3 - \sqrt{2-b^2}s_5\right)\right)\right\}\\ &-\sqrt{2}\mathrm{Re}\left\{r_1\left(h_1^*(s_1 - as_3) - h_2^*(s_1 + as_3)\right)\right\}\\ &+\left(|h_1|^2 + |h_2|^2\right)\left(|s_1|^2 + |as_3|^2 + \left|\sqrt{2-b^2}s_5\right|^2\right)\\ &+(as_1s_3)\left(|h_2|^2 - |h_1|^2\right)\\ &+\left(\sqrt{2-b^2}s_1s_5\right)\left(|h_2|^2 - |h_1|^2\right) + \left(a\sqrt{2-b^2}s_3s_5\right)\left(|h_1|^2 - |h_2|^2\right)\end{aligned} \quad (23)$$

$$\begin{aligned}f_I(s_2,s_4,s_6) = &-\sqrt{2}\mathrm{Re}\left\{jr_3\left(h_1^*(s_2 - bs_6) + h_2^*(bs_6 + s_2)\right)\right\}\\ &-\sqrt{2}\mathrm{Re}\left\{jr_2\left(h_1^*\left(-\sqrt{2-a^2}s_4 - bs_6\right)\right.\right.\\ &\left.\left.+ h_2^*\left(\sqrt{2-a^2}s_4 - bs_6\right)\right)\right\}\\ &-\sqrt{2}\mathrm{Re}\left\{jr_1\left(h_1^*\left(\sqrt{2-a^2}\,s_4 - s_2\right)\right.\right.\\ &\left.\left.- h_2^*\left(s_2 + \sqrt{2-a^2}s_4\right)\right)\right\}\\ &+\left(|h_1|^2 + |h_2|^2\right)\left(|s_2|^2 + \left|\sqrt{2-a^2}s_4\right|^2 + |bs_6|^2\right)\\ &+\left(\sqrt{2-a^2}s_2s_4\right)\cdot\left(|h_2|^2 - |h_1|^2\right)\\ &+(bs_2s_6)\left(|h_2|^2 - |h_1|^2\right) + \left(b\sqrt{2-a^2}s_4s_6\right)\left(|h_1|^2 - |h_2|^2\right) \quad (24)\end{aligned}$$

where r_i is the received signal at the ith time slot.

It is clear that the minimization of the metric is equivalent to minimization of f_R and f_I independently. Therefore, the ML decoding of the proposed code requires a joint detection of three real symbols, that is, the complexity is of order $O(M^{1.5})$ for square symbol constellation. For non-square symbol constellations, in which $M = M_R M_I$, where M_R and M_I are the sizes of the real and imaginary parts of constellation, respectively, the complexity is of order $O((\max(M_R, M_I))^3)$.

IV. Performance Evaluation

We evaluate the performance of the proposed code in terms of BER, detection complexity, peak to average power ratio (PAPR) [11], MDV, and trace criterion. In the simulations, we assume $E[|x_i|^2] = 1$ and the normalization is imposed on q (eq. (1)).

Because of the low performance of Alamouti [5] and AL codes [4] (hybrid scheme), the results of these codes are not depicted. Moreover, it has been shown in [7] and [8] that the code in [6] has higher BER than [7] and [8]. In addition, it has higher

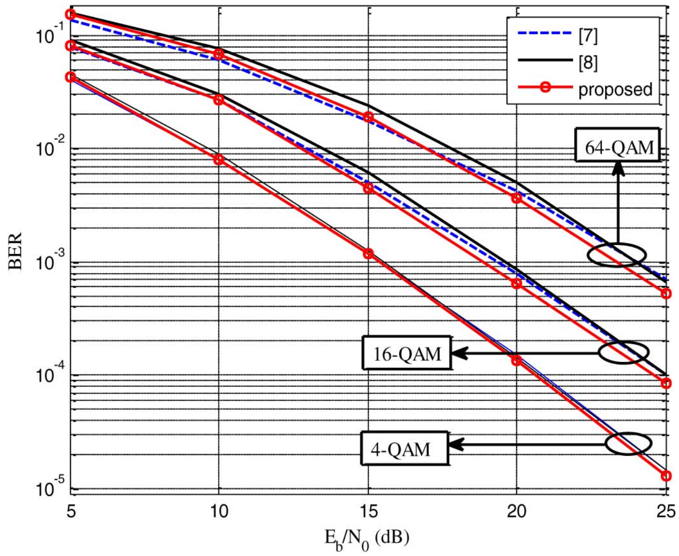

Fig. 1. BER curves of the proposed code, GSTBC [7], and [8] for 2, 4, and 6 bpcu by 4-QAM, 16-QAM, and 64-QAM, respectively.

TABLE I
DETECTION COMPLEXITY OF DIFFERENT CODES

Code	[7]	[8]	Proposed
Complexity	$O(M^1)$	$O(M^{1.5})$	$O(M^{1.5})$

detection complexity, $(O(M^2))$. Therefore, we compare the proposed code with those of [7] and [8].

Fig. 1 shows the BER curves where we have considered 2, 4, and 6 bits per channel usage (bpcu), i.e., throughput, using 4-QAM, 16-QAM, and 64-QAM constellations, respectively. We observe that our code has lower BER than [7] at high SNRs and outperforms [8] (and consequently [6]) in all SNRs.

Table I shows the detection complexity of different codes and Table II demonstrates the PAPRs of the codes for various constellations where PAPR is computed using eq. (2) of [11].

The group decodable code [7] shown in (25) utilizes constellation rotation to achieve better BER performance. In this code complexity is the main factor (group decodability).

$$\mathbf{X}_{[7]} = \begin{bmatrix} s_1+s_2+js_3+js_4 & s_5+js_6 \\ -s_5+js_6 & s_1+s_2-js_3-js_4 \\ -s_1+s_2-js_3+js_4 & -s_1+s_2-js_3+js_4 \end{bmatrix} \quad (25)$$

From the group decodability aspect, the proposed code is also two group decodable where there are three real symbols in each group. According to the notation of [7], the group matrices of our code can be written as

$$\begin{aligned} &\{\mathbf{C}_{I,1},\mathbf{C}_{I,2},\mathbf{C}_{I,3}\},\{\mathbf{C}_{II,1},\mathbf{C}_{II,2},\mathbf{C}_{II,3}\}_p \\ &=\left\{\frac{1}{\sqrt{2}}\begin{bmatrix}1&1\\0&0\\-1&1\end{bmatrix},\frac{a}{\sqrt{2}}\begin{bmatrix}-1&1\\1&1\\0&0\end{bmatrix},\frac{\sqrt{2-b^2}}{\sqrt{2}}\begin{bmatrix}0&0\\1&-1\\1&1\end{bmatrix}\right\}, \\ &\left\{\frac{j}{\sqrt{2}}\begin{bmatrix}1&-1\\0&0\\-1&-1\end{bmatrix},\frac{j\sqrt{2-a^2}}{\sqrt{2}}\begin{bmatrix}-1&-1\\1&-1\\0&0\end{bmatrix},\frac{jb}{\sqrt{2}}\begin{bmatrix}0&0\\1&1\\1&-1\end{bmatrix}\right\} \end{aligned} \quad (26)$$

for s_1, s_3, s_5, s_2, s_4, and s_6, respectively.

TABLE II
PAPR OF DIFFERENT CODES

Code	[7]	[8]	Proposed
4-QAM	1.88	1.98	1.98
16-QAM	2.6	3.57	3.57
64-QAM	4.44	4.63	4.63

TABLE III
MDV AND TRACE VALUE OF THE PROPOSED CODE AND [8]

Code	[8]	Proposed
MDV	5.82	7.39
Trace	4.85	5.44

TABLE IV
REQUIRED E_b/N_0 (dB) TO ACHIEVE THE SAME BER FOR DIFFERENT CODES AND DIFFERENT bpcus

code	[7]	[8]	proposed
BER=2×10^{-5} 4-QAM (2 bpcu)	24.32	24.32	24.2
BER=2×10^{-4} 16-QAM (4 bpcu)	23.33	23.4	22.89
BER=2×10^{-3} 64-QAM (6 bpcu)	22.01	22.28	21.56

The amounts of minimum determinant and minimum trace of [7] for 4-QAM are 16 and 8, respectively, that are higher than those of the proposed code (7.39, 5.44). However, our code has lower BER than [7] at high SNRs. This is because of diagonal property of $\bar{\mathbf{X}}_p^H\bar{\mathbf{X}}_p$ that is also a part of trace criterion [9], [10]. Unlike our code, the code in [7] does not have non-vanishing property. The detection complexity of the proposed code is slightly higher than [7].

In the code of [8] each symbol is placed in three entries of the encoding matrix as depicted in (27). It uses stretching technique to achieve full diversity and high coding gain. It has detection complexity of order $O(M^{1.5})$ which is the same as our code. $\bar{\mathbf{X}}_{[8]}^H\bar{\mathbf{X}}_{[8]}$ matrix is diagonal. In [8], the PAPRs of the two antennas differ, while they are the same in our code. However, the two codes have the same PAPR. This code and our code have non-vanishing property. Table III shows the MDV and minimum trace value of the two codes. We observe that the minimum trace and minimum determinant of the proposed code are higher than those of [8], which result in lower BER of our code.

$$\mathbf{X}_{[8]} = \begin{bmatrix} x_1 & (-x_2^*-x_3^*)/\sqrt{2} \\ x_2 & (x_1^*-x_3^*)/\sqrt{2} \\ x_3 & (x_1^*+x_2^*)/\sqrt{2} \end{bmatrix} \quad (27)$$

Table IV demonstrates the required SNRs to achieve specified BERs for different codes and throughputs. It is observed that the proposed code has better performance.

V. CONCLUSION

In this paper, we proposed an efficient STBC scheme for three time slots and two transmit antennas. The detection complexity of the proposed scheme for square symbol constellation is lower than [6], slightly higher than [7], and equal to [8]. The results show that our code has lower BER than [7] at high SNRs and outperforms [8] and [6] in all SNRs. Further, it has non-vanishing property.

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