A Novel Spatially-Modulated Orthogonal Space-Time Block Code For 4 Transmit Antennas

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***Abstract*—This paper presents a novel Spatially Modulated Orthogonal Space-Time Block Coding (SM-OSTBC) scheme for 4 transmit antennas based on the concept of Spatial Constellation (SC) first proposed in [1]. In the scheme, transmit SM-OSTBC codewords are generated simply by multiplying SC codewords with OSTBC codewords. An optimization technique for the SM-OSTBC scheme to achieve a transmit diversity order of 3 is discussed. In addition, a simple maximum-likelihood (ML) decoder is derived. BER performance of the proposed scheme is evaluated via computer simulation and theoretical upper bound. It is shown that the proposed scheme outperforms various existing MIMO transmission counterparts in a number of application scenarios.**

I. Introduction

Multiple-input multiple-output (MIMO) systems have been theoretically and practically shown to significantly improve spectral efficiency of wireless communication systems [2]–[3]. Two main MIMO transmission strategies, which attract intensive research, are space-time block coding (STBC)[1] and spatial multiplexing. The aim of STBC is to reduce bit error rate of a wireless system by means of transmit diversity. On the other hand, spatial multiplexing aims at improving spectral efficiency, and thus data rate.

Orthogonal space-time block codes are attractive class of STBCs for realizing transmit diversity due to their full diversity and their simple decoding algorithms [4]–[7]. Unfortunately, rate-one full diversity OSTBC exists only for 2 transmit antennas. The maximum symbol rate of OSTBC is limited at $3/4$ symbol per channel use for more than 2 transmit antennas [5].

In contrast to OSTBCs, spatial multiplexing is developed in order to meet the demand for high data rates in modern wireless communication systems. A well-known spatial multiplexing scheme is the Vertical Bell Layered Space Time (V-BLAST) system [8]. In this system, independent co-channel signals are transmitted simultaneously from different transmit antennas, thus increasing the spectral efficiency in proportion to the number of transmit antennas, n_T. However, V-BLAST creates a high level of inter-channel interference (ICI) at the receiver, thereby causing complexity of optimal maximum likelihood (ML) decoder to grow exponentially with n_T. The use of sub-optimal decoder, such as zero forcing (ZF) or the minimum mean square error (MMSE) decoder, allows low detection complexity at the expense of significant BER performance reduction.

In recent publication, Mesleh *et al.* introduced a novel concept called spatial modulation (SM), which increases spectral efficiency without creating ICI [9]. In SM transmission schemes, the information data is conveyed by both the conventional amplitude/phase modulation (APM) techniques and antenna indices. Here, ICI interference is completely eliminated by activating only one transmit antenna during each transmission interval. Similar to V-BLAST systems, the SM systems aim at exploiting multiplexing gain without considering to utilize the transmit diversity gain of MIMO systems.

In [10], Başar *et al.* introduced Space-Time Block Coded Spatial Modulation (STBC-SM), which was designed to take advantage of SM as well as STBC. In a STBC-SM system, both STBC symbols and the indices of transmit antennas, from which these STBC symbols are transmitted, bear information. Due to its simplicity in detection and full rate (i.e., rate one), Alamouti's STBC has been chosen to be the core STBC. Accordingly, at each symbol period, two (among n_T) transmit antennas are activated for signal transmission. As a consequence, the total number of STBC-SM codewords is equal to $c = \left\lfloor \binom{n_T}{2} \right\rfloor_{2^p}$, where p is a positive integer, and the resulting spectral efficiency of the STBC-SM scheme is $m = \frac{1}{2}\log_2 c + \log_2 M$ (bits/s/Hz), where M is the constellation size [10]. That is, an increase of $\frac{1}{2}\log_2 c$ (bits/s/Hz) in the spectral efficiency is obtained as compared to the Alamouti's scheme.

In this paper, we utilize the concepts of Spatial Constellation (SC) and SC codewords, introduced in [1], to propose a novel *Spatial Modulated Orthogonal Space-Time Block Coding (SM-OSTBC)* scheme for 4 transmit antennas. It is worth noting that the proposed approach is not limited to 4 transmit antennas and could be generalized to the case of any number of transmit antennas. The OSTBC of interest is the one devised for 3 transmit antennas with rate $\frac{3}{4}$ symbols per channel [6]-[7]. In the proposed scheme, transmitted codeword matrices (i.e, SM-OSTBC codewords) are generated simply by multiplying SC codeword matrices with OSTBC matrices.

The contributions of this paper can be summarized as

[1]Depending on the context, "STBC(s)" can be interpreted as space-time block coding/codes

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follows:

- A SM-OSTBC system with 4 transmit antennas is presented. The number of designed SC codewords is equal to 16, leading to an increases of 1 bit/s/Hz in spectral efficiency as compared to the original OSTBC scheme.
- Using the SC codewords and the orthogonality of the OSTBC, a low-complexity ML decoder is devised for the proposed SM-OSTBC scheme.
- A theoretical union bound on the bit error rate of the SM-OSTBC scheme is derived, which then can be used as a means to evaluate BER performance of the SM-OSTBC in sufficiently high signal-to-noise power ratio (SNR) regions.
- Computer simulation results, supported by the derived theoretical upper bound, are provided to demonstrate the BER performance of the proposed SM-OSTBC scheme in comparison with those of existing MIMO transmission schemes, such as the Alamouti's STBC, the V-BLAST, the SM and the STBC-SM.

The rest of the paper is organized as follows. Section II presents system model. In section III, the proposed SC codewords for 4 transmit antennas are shown. We analyze performance of proposed schemes using union bound in Section IV. Section V provides simulation results and performance comparison. The final section concludes this paper.

II. System Model and Spatial Constellation Concept

A. System Model

Consider the rate $\frac{3}{4}$ OSTBC for 3 transmit antennas with the following 3×4 codeword matrix [6]-[7]:

$$\mathbf{X} = \begin{bmatrix} x_1 & -x_2^* & -x_3^* & 0 \\ x_2 & x_1^* & 0 & -x_3^* \\ x_3 & 0 & x_1^* & x_2^* \end{bmatrix} \quad (1)$$

whose entries are drawn from M-QAM or M-PSK constellation Ω_M. Let $\mathbf{S}$ be a 4×3 SM codeword matrix, then the SM-OSTBC transmitter generates the 4×4 SM-OSTBC codeword matrix $\mathbf{C}$ as [1]:

$$\mathbf{C} = \mathbf{SX} \quad (2)$$

The matrix $\mathbf{C}$ is transmitted via 4 transmit antennas within 4 symbol periods. At the receiver, the received $n_R \times 4$ signal matrix $\mathbf{Y}$ is given by:

$$\begin{aligned} \mathbf{Y} &= \sqrt{\gamma}\mathbf{HC} + \mathbf{N} \\ &= \sqrt{\gamma}\mathbf{HSX} + \mathbf{N} \end{aligned} \quad (3)$$

where $\mathbf{H}$ and $\mathbf{N}$ respectively denote $n_R \times 4$ channel matrix and $n_R \times 4$ noise matrix. The entries of $\mathbf{H}$ and $\mathbf{N}$ are assumed to be independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance. Besides, $\mathbf{H}$ is assumed to remain constant within a codeword of 4 symbol periods and changes independently from one codeword to another. The transmit codeword $\mathbf{C}$ is normalized such that the ensemble average of the trace of $\mathbf{C}^H\mathbf{C}$ is equal to 3, i.e., $E\{\text{tr}(\mathbf{C}^H\mathbf{C})\} = 3$. γ is the average SNR at each receive antenna.

III. Proposed SM Codewords and Signal Detection

A. Design of SC codeword matrices

As modeled above, SM-OSTBC codewords are obtained by multiplying the SC codewords with the core OSTBC one. Since the core OSTBC codeword is already available in (1), this section will present the design of SC codewords for the proposed SM-OSTBC scheme.

Let us define a codeword difference matrix $\mathbf{D}(\mathbf{C}_m, \mathbf{C}_n)$ between the two SM-OSTBC codewords $\mathbf{C}_m$ and $\mathbf{C}_n$ as:

$$\mathbf{D}(\mathbf{C}_m, \mathbf{C}_n) = \mathbf{C}_m - \mathbf{C}_n \quad (4)$$

Based on the rank and determinant criteria [11], the design criterion for the SC codewords can be summarized as follows:

- The rank of the matrix $\mathbf{Q}(\mathbf{C}_m, \mathbf{C}_n) = \mathbf{D}^H(\mathbf{C}_m, \mathbf{C}_n)\mathbf{D}(\mathbf{C}_m, \mathbf{C}_n)$ is equal to 3 over all pairs of distinct SM-OSTBC codewords.
- The minimum product, $\delta_{\min} = \prod_{i=1}^{3} \lambda_i$, of the matrix $\mathbf{Q}(\mathbf{C}_m, \mathbf{C}_n)$ is maximized among all pairs of distinct SM-OSTBC codewords, where λ_i are the non-zero eigenvalues of $\mathbf{Q}(\mathbf{C}_m, \mathbf{C}_n)$.

Based on the complex OSTBC for 3 transmit antennas [5]-[7], we define the following 4×3 basic matrices:

$$\mathbf{G}_1(\mathbf{s}) = \frac{1}{\Gamma} \begin{bmatrix} s_1 & 0 & s_2 \\ 0 & s_1 & s_3^* \\ -s_2^* & -s_3 & s_1^* \\ s_3^* & -s_2 & 0 \end{bmatrix} \quad (5)$$

$$\mathbf{G}_2(\mathbf{s}) = \frac{1}{\Gamma} \begin{bmatrix} s_1 & s_2 & \frac{s_3}{\sqrt{2}} \\ -s_2^* & s_1^* & \frac{s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} & \frac{-s_1 - s_1^* + s_2 - s_2^*}{2} \\ \frac{s_3^*}{\sqrt{2}} & \frac{-s_3^*}{\sqrt{2}} & \frac{s_1 - s_1^* + s_2 + s_2^*}{2} \end{bmatrix} \quad (6)$$

$$\mathbf{G}_3(\mathbf{s}) = \frac{1}{\Gamma} \begin{bmatrix} s_2 & \frac{s_3}{\sqrt{2}} & \frac{s_3}{\sqrt{2}} \\ s_1^* & \frac{s_3}{\sqrt{2}} & \frac{-s_3}{\sqrt{2}} \\ \frac{s_3^*}{\sqrt{2}} & \frac{-s_1 - s_1^* + s_2 - s_2^*}{2} & \frac{s_1 - s_1^* - s_2 - s_2^*}{2} \\ \frac{-s_3^*}{\sqrt{2}} & \frac{s_1 - s_1^* + s_2 + s_2^*}{2} & \frac{-s_1 - s_1^* - s_2 + s_2^*}{2} \end{bmatrix} \quad (7)$$

where $\mathbf{s} = \begin{bmatrix} s_1 & s_2 & s_3 \end{bmatrix}$ is a 1×3 vector with complex entries s_i, $i = 1, 2, 3$; s_i^* is the complex conjugate of s_i; and $\Gamma = \|\mathbf{s}\| = \sqrt{|s_1|^2 + |s_2|^2 + |s_3|^2}$ is the magnitude of $\mathbf{s}$, which is used as a normalization factor to meet the transmit power constraint.

Using trial–and–error method with computer-aided to calculate the minimum product $\delta_{\min}$, we obtain the spatial constellation, Ω_S, with $K = 16$ SC codewords for the proposed SM-OSTBC scheme as follows:

$$\begin{aligned} \mathbf{S}_1 &= \mathbf{G}_1\left(\begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\right) \\ \mathbf{S}_2 &= \mathbf{G}_1\left(\begin{bmatrix} 1 & 1 & 0 \end{bmatrix}\right) \\ \mathbf{S}_3 &= \mathbf{G}_1\left(\begin{bmatrix} 1 & 1 & 1 \end{bmatrix}\right) \\ \mathbf{S}_4 &= \mathbf{G}_1\left(\begin{bmatrix} 1 & j & 0 \end{bmatrix}\right) \\ \mathbf{S}_5 &= \mathbf{G}_2\left(\begin{bmatrix} 1 & 1 & 0 \end{bmatrix}\right) \\ \mathbf{S}_6 &= \mathbf{G}_2\left(\begin{bmatrix} 1 & 1 & 1 \end{bmatrix}\right) \end{aligned}$$

$$\mathbf{S}_7 = \mathbf{G}_2\left(\left[\begin{array}{ccc} 1 & 1 & -1 \end{array}\right]\right)$$
$$\mathbf{S}_8 = \mathbf{G}_2\left(\left[\begin{array}{ccc} 1 & -1 & 1 \end{array}\right]\right)$$
$$\mathbf{S}_9 = \mathbf{G}_2\left(\left[\begin{array}{ccc} 1 & -1 & -1 \end{array}\right]\right)$$
$$\mathbf{S}_{10} = \mathbf{G}_3\left(\left[\begin{array}{ccc} 1 & 1 & 0 \end{array}\right]\right)$$
$$\mathbf{S}_{11} = \mathbf{G}_3\left(\left[\begin{array}{ccc} 1 & j & 0 \end{array}\right]\right)$$
$$\mathbf{S}_{12} = \mathbf{G}_3\left(\left[\begin{array}{ccc} 1 & -j & 1 \end{array}\right]\right)$$
$$\mathbf{S}_{13} = \mathbf{G}_3\left(\left[\begin{array}{ccc} -1 & -j & 1 \end{array}\right]\right)$$
$$\mathbf{S}_{14} = \mathbf{G}_3\left(\left[\begin{array}{ccc} j & -1 & -1 \end{array}\right]\right)$$
$$\mathbf{S}_{15} = \mathbf{G}_3\left(\left[\begin{array}{ccc} j & 1 & 1 \end{array}\right]\right)$$
$$\mathbf{S}_{16} = \mathbf{G}_3\left(\left[\begin{array}{ccc} 1 & 0 & 1 \end{array}\right]\right)$$

where $j = \sqrt{-1}$.

Computer search results show that the SM-OSTBC has $\delta_{\min} = 4.15$ for QAM modulation. Therefore, the SM-OSTBC system always achieves a diversity order of $3n_R$. In addition, the SM-OSTBC's spectral efficiency is equal to $e = \left(1 + \frac{3}{4}\log_2 M\right)$ [bits/s/Hz] for M-QAM modulation, i.e., an increase of 1 bits/s/Hz compared to the spectral efficiency of the rate 3/4 OSTBC in (1).

B. Optimal ML Detection of the proposed SM-OSTBC scheme

Assuming that perfect channel state information is available at the receiver. An optimal ML decoder for the proposed STBC-SM scheme exhaustively search over all codewords $\mathbf{S}$ in spatial constellation Ω_S and codewords $\mathbf{X}$ in the OSTBC codeword space Ω_X and chooses the pair of matrices $(\hat{\mathbf{S}}, \hat{\mathbf{X}})$ that satisfies the following ML decoding rule:

$$(\hat{\mathbf{S}}, \hat{\mathbf{X}}) = \arg\min_{\mathbf{S}\in\Omega_S, \mathbf{X}\in\Omega_X} \left\|\mathbf{Y} - \sqrt{\gamma}\mathbf{HSX}\right\|^2 \tag{8}$$

For a given matrix $\mathbf{S}_k \in \Omega_S, k = 1, \cdots, K$, we have a corresponding $n_R \times 3$ equivalent matrix $\tilde{\mathbf{H}}_k = \mathbf{HS}_k$, then the system in (3) becomes the conventional OSTBC system for 3 transmit antennas:

$$\mathbf{Y} = \sqrt{\gamma}\tilde{\mathbf{H}}_k\mathbf{X} + \mathbf{N} \tag{9}$$

Equation (9) can be reorganized as [12]:

$$\mathbf{y} = \sqrt{\gamma}\mathcal{H}_k \left[\begin{array}{c} x_1 \\ x_2 \\ x_3 \end{array}\right] + \mathbf{n} \tag{10}$$

where $\mathcal{H}_k$ is of the form

$$\mathcal{H}_k = \left[\begin{array}{ccc} \tilde{h}_{11,k} & \tilde{h}_{12,k} & \tilde{h}_{13,k} \\ \tilde{h}^*_{12,k} & -\tilde{h}^*_{11,k} & 0 \\ \tilde{h}^*_{13,k} & 0 & -\tilde{h}^*_{11,k} \\ 0 & \tilde{h}^*_{13,k} & -\tilde{h}^*_{12,k} \\ \vdots & \vdots & \vdots \\ \tilde{h}_{n_R 1,k} & \tilde{h}_{n_R 2,k} & \tilde{h}_{n_R 3,k} \\ \tilde{h}^*_{n_R 2,k} & -\tilde{h}^*_{n_R 1,k} & 0 \\ \tilde{h}^*_{n_R 3,k} & 0 & -\tilde{h}^*_{n_R 1,k} \\ 0 & \tilde{h}^*_{n_R 3,k} & -\tilde{h}^*_{n_R 2,k} \end{array}\right] \tag{11}$$

$$= \left[\begin{array}{ccc} \mathbf{h}_{1,k} & \mathbf{h}_{2,k} & \mathbf{h}_{3,k} \end{array}\right] \tag{12}$$

Due to the pair-wise orthogonality of the three columns $\mathbf{h}_{1,k}$, $\mathbf{h}_{2,k}$, and $\mathbf{h}_{3,k}$ of $\mathcal{H}_k$, x_1, x_2, and x_3 can be detected independently. The decoding process can be summarized as follows.

- For each matrix $\mathcal{H}_k$ and for each symbol $x_{i,m}, i = 1, 2, 3$, in the transmit constellation, compute the following Euclidean distances:
  - $d^m_{i,k} = \left\|\mathbf{y} - \sqrt{\gamma}\mathbf{h}_{i,k}x_{i,m}\right\|^2$, for $m = 1, \cdots, M$.
- Find $d^{\min}_{i,k}$ among M values of $d^m_{i,k}$ and $\hat{x}^k_i$ corresponding to $d^{\min}_{i,k}$.
- Calculate $d_k = \sum_{i=1}^3 d^{\min}_{i,k}$, for $k = 1, \cdots, K$.
- Find index $\hat{k}$ corresponding to the minimum distance $d^{\min}_k$ among K values of d_k.
- The estimated SC matrix and transmitted symbols are given by: $\hat{\mathbf{S}} = \mathbf{S}_{\hat{k}}$, $\hat{x}_i = \hat{x}^{\hat{k}}_i, i = 1, 2, 3$.

The above decoder is optimal in the sense that it and the ML decoder in (8) provide identical BER performance for the same operation conditions.

IV. Performance Evaluation of the Proposed SM-OSTBC

In this section, we investigate error performance of the proposed SM-OSTBC scheme via their pairwise error probability (PEP) and an upper bound for the bit error probability.

The PEP $P(\mathbf{C}_i \to \mathbf{C}_j)$ is the probability of deciding codeword $\mathbf{C}_j$ given that codeword $\mathbf{C}_i$ is transmitted. The PEP, conditioned on the channel $\mathbf{H}$, is given by [11]:

$$P(\mathbf{C}_i \to \mathbf{C}_j|\mathbf{H}) = Q\left(\sqrt{\frac{\gamma}{2}d^2(\mathbf{C}_i, \mathbf{C}_j)}\right) \tag{13}$$

where $Q(y) = \frac{1}{\sqrt{2\pi}}\int_y^\infty e^{-\frac{1}{2}x^2}dx$ is the Gaussian tail probability, and $d^2(\mathbf{C}_i, \mathbf{C}_j)$ is the modified Euclidean distance between $\mathbf{C}_i$ and $\mathbf{C}_j$. Under the assumption that the channel is a slow fading one, $d^2(\mathbf{C}_i, \mathbf{C}_j)$ is given by [11], [13]:

$$d^2(\mathbf{C}_i, \mathbf{C}_j) = \sum_{k=1}^{n_T}\sum_{l=1}^{n_R}\lambda_k|\beta_{k,l}|^2 \tag{14}$$

where λ_k, $k = 1, \cdots, n_T$ denotes the eigenvalues of the codeword distance matrix $\mathbf{C}_\Delta = (\mathbf{C}_i - \mathbf{C}_j)^H(\mathbf{C}_i - \mathbf{C}_j)$. $\beta_{k,l}$'s are independent complex Gaussian random variables with a zero mean and unit variance. Since $\mathbf{C}_\Delta$ is nonnegative-definite Hermitian matrix [11], $\lambda_k \geq 0$.

Using the alternative form of $Q(x)$ by Craig, we can write [13]

$$\begin{aligned} P(\mathbf{C}_i \to \mathbf{C}_j|\mathbf{H}) &= \frac{1}{\pi}\int_0^{\pi/2}\exp\left[-\frac{\gamma d^2(\mathbf{C}_i, \mathbf{C}_j)}{4\sin^2\theta}\right]d\theta \\ &= \frac{1}{\pi}\int_0^{\pi/2}\prod_{k=1}^{r}\prod_{l=1}^{n_R}\exp\left[-\frac{\gamma\lambda_k|\beta_{k,l}|^2}{4\sin^2\theta}\right]d\theta \end{aligned} \tag{15}$$

where r is the number of non-zero eigenvalues among n_T eigenvalues of $\mathbf{C}_\Delta$. For the proposed SM-OSTBC, $r = 3$. By averaging (15) over the channel matrix $\mathbf{H}$, or equivalently over

$|\beta_{k,l}|^2$ with chi-square distribution, we obtain the PEP of the SM-OSTBC as [13]:

$$P(\mathbf{C}_i \to \mathbf{C}_j) = \frac{1}{\pi}\int_0^{\pi/2}\prod_{k=1}^{r}\left[1+\frac{\gamma\lambda_k}{4\sin^2\theta}\right]^{-n_R} d\theta$$
$$= \frac{1}{\pi}\int_0^{\pi/2}\prod_{k=1}^{3}\left[1+\frac{\gamma\lambda_k}{4\sin^2\theta}\right]^{-n_R} d\theta \quad (16)$$

Assuming that b information bits are transmitted using one of a total $N = KM^2$ SM-OSTBC codeword matrices $\mathbf{C}_1, \mathbf{C}_2, \cdots, \mathbf{C}_N$, i.e., $b = \log_2 N$. Then, using the PEP in (16), an upper bound for the average bit error probability (BEP) of the proposed SM-OSTBC systems is given by [14]:

$$P_b \leq \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{P(\mathbf{C}_i \to \mathbf{C}_j)w_{i,j}}{b} \quad (17)$$

where $w_{i,j}$ is the number of error bits, caused by detecting $\mathbf{C}_j$ when $\mathbf{C}_i$ is transmitted. In fact, $w_{i,j}$ is Hamming distance between the two codewords $\mathbf{C}_i$ and $\mathbf{C}_j$.

Since $P(\mathbf{C}_i \to \mathbf{C}_j) = P(\mathbf{C}_j \to \mathbf{C}_i), w_{i,j} = w_{j,i}$, and $w_{i,i} = 0$, the upper bound in (17) reduces to:

$$P_b \leq \frac{2}{bN}\sum_{i=1}^{N-1}\sum_{j=i}^{N}P(\mathbf{C}_i \to \mathbf{C}_j)w_{i,j} \quad (18)$$

V. Simulation Results and Discussions

In this section, we use theoretical upper bound given in (18) and Monte Carlo simulations to verify BER performance of the proposed SM-OSTBC schemes and make comparisons with various existing MIMO systems including: the Alamouti's STBC [4], the OSTBC for 4 transmit antennas with rate 1/2 (OSTBC 1/2) [5] and rate 3/4 (OSTBC 3/4) [6]-[7], V-BLAST [8], high rate STBC-SM (HR-STBC-SM) for 4 transmit antennas [1], STBC-SM [10], and SM [9]. For convenience, a MIMO system with n_T transmit antennas and n_R receive antennas is referred to as (n_T, n_R) system.

Illustrated in Fig. 1 are the BER performance curves of the proposed SM-OSTBC in (4, 2) and (4, 4) systems using 4-QAM modulation. As a reference, the BEP upper bound curves are also evaluated using (18) and presented in the same figure. We can see from Fig. 1 that as the number of receive antenna increases and the signal to noise power ratio (SNR) is high enough, theoretical and simulation results become very close. Consequently, the bound in (18) can be used as a means to study performance behavior of the SM-OSTBC in sufficiently high SNR regions.

In Fig. 2, we compare BER performance of our proposed SM-OSTBC with those of HR-STBC-SM, OSTBC 1/2, and OSTBC 3/4 in (4, 2) and (4, 4) systems. In the simulation, SM-OSTBC scheme uses 4-QAM modulation, while HR-STBC-SM and OSTBC 1/2 respectively utilize BPSK and 32-QAM to deliver the same spectral efficiency of 2.5 bits/s/Hz. Since it is unable to obtain 2.5 bits/s/Hz with OSTBC 3/4, 8-QAM modulation is applied to achieve 2.25 bits/s/Hz. It is seen that when $n_R = 2$, SM-OSTBC remarkably outperforms OSTBC

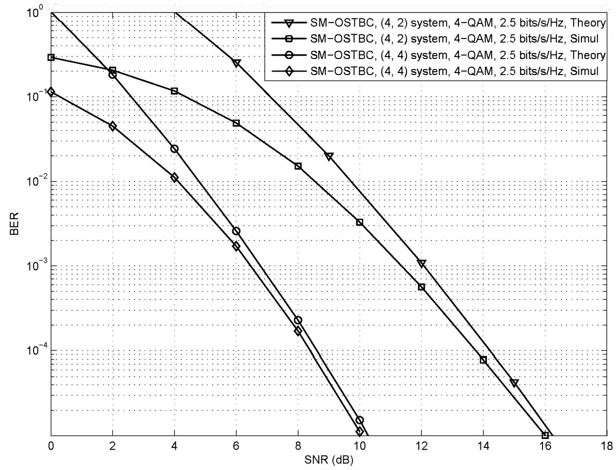

Fig. 1. Theoretical upper bounds and simulation results of BER performance of the proposed SM-OSTBC scheme for different numbers of receive antennas.

1/2 and HR-STBC-SM with SNR gains of approximately 3.6 dB and 2.3 dB at BER = 10^{-5}. Furthermore, compared to OSTBC 3/4, SM-OSTBC offers both spectral efficiency improvement of 0.25 bits/s/Hz and SNR gain of about 0.5 dB. When n_R increases from 2 to 4, SM-OSTBC still has higher BER performance than do its three counterparts. Particularly, performance gap between SM-OSTBC and OSTBC 1/2 and that between SM-OSTBC and OSTBC 3/4 at BER = 10^{-5} are widen with the differences of about 4.8 dB and 1.3 dB, correspondingly. In contrast, performance gap between SM-OSTBC and HR-STBC-SM reduces from about 2.3 dB to around 0.5 dB.

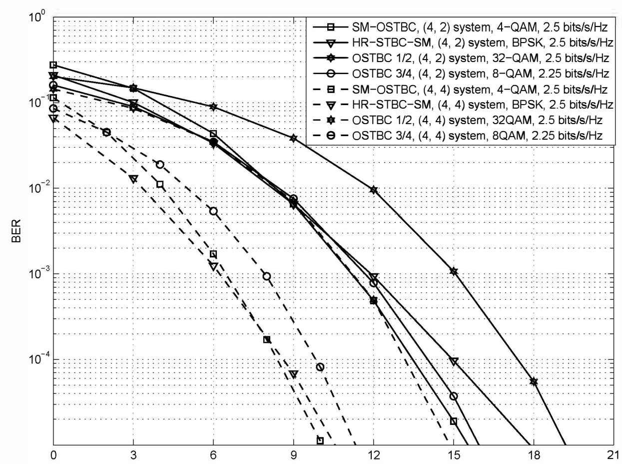

Fig. 2. BER curves of the proposed SM-OSTBC, HR-STBC-SM, and OSTBC 1/2 at 2.5 bits/s/Hz and OSTBC 3/4 at 2.25 bits/s/Hz in (4, 2) and (4, 4) systems.

Fig. 3 shows BER performances of the proposed SM-OSTBC, SM, VBLAST, and STBC-SM in (4, 2) and (4, 4) systems and the Alamouti's STBC in (2, 2) and (2, 4) systems. The proposed and the Alamouti's schemes adopts 16-QAM modulation, whereas the SM, VBLAST and STBC-SM use 4-QAM, BPSK and 8-QAM, respectively. Note that signal detection in the VBLAST system is maximum likelihood based on the QMLD decoder [15]. All 5 systems have a spectral efficiency of 4 bits/s/Hz.

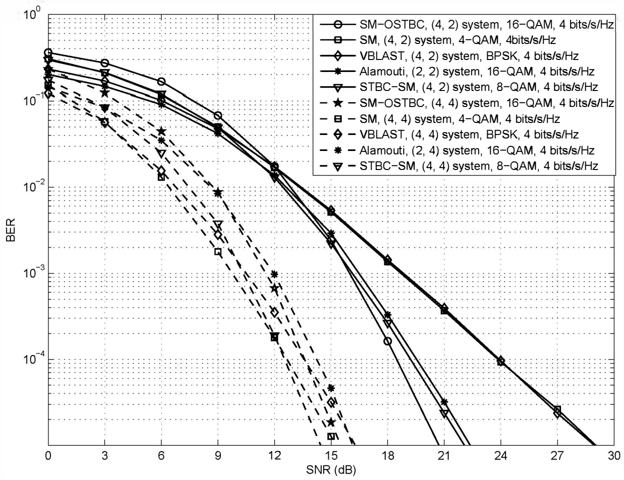

Fig. 3. BER curves of the proposed SM-OSTBC in comparison with those of SM, VBLAST, the Alamouti's STBC, and STBC-SM; 4 bits/s/Hz.

From Fig. 3 it is again seen that the proposed SM-OSTBC significantly outperforms SM, VBLAST, the Alamouti's STBC, and STBC-SM when $n_R = 2$. At BER = 10^{-5}, SM-OSTBC gains about 8.2 dB in SNR compared to both SM and VBLAST, and about 1.3 dB and 1.6 dB compared to STBC-SM and the Alamouti's STBC, respectively. However, as n_R increases to 4, SM-OSTBC just offers small SNR gains of roughly 0.7 dB and 0.6 dB when comparing with BER performances of VBLAST and the Alamouti's STBC, respectively. It even underperforms SM and STBC-SM by about 0.25 dB and 1 dB in SNR at BER = 10^{-5}, correspondingly.

It can be inferred from both Fig. 2 and Fig. 3 that although the SM-OSTBC is able to achieve a diversity order of $3n_R$, its capacity is still very far from that of a (n_T, n_R) MIMO system. As a consequence, for a small spectral efficiency and a small number of receive antennas, the SM-OSTBC scheme outperforms other existing MIMO schemes under consideration due to its high diversity gain. For a large spectral efficiency and large a number of receive antennas, the SM-OSTBC scheme will underperform high rate MIMO transmission schemes such as SM, VBLAST, HR-STBC-SM, or STBC-SM due to its inferior capacity.

VI. Conclusion

In this paper, we utilized the concept of Spatial Constellation and Spatial Constellation codewords, introduced in [1], to propose a novel high-performance and low complexity MIMO transmission scheme, called SM-OSTBC. The system is built based on the rate $\frac{3}{4}$ OSTBC for 3 transmit antennas and able to deliver an additional spectral efficiency of 1 bits/s/Hz compared to the rate $\frac{3}{4}$ OSTBC. In addition, the SM-OSTBC was shown to achieve a diversity order of $3n_R$. We employed the orthogonality of the OSTBC to develop a simple ML decoder for signal recovery. It has been shown via simulation results that, for small spectral efficiencies and small numbers of receive antennas, the proposed SM-OSTBC offers significant improvements in BER performance compared to OSTBC 1/2, OSTBC 3/4, the Alamouti's STBC, SM, STBC-SM, and HR-STBC-SM. On the contrary, it will be outperformed by SM, STBC-SM, HR-STBC-SM or by VBLAST when large spectral efficiency is required and more receive antennas are available. This is the first step to apply the concept of spatial constellation to high diversity order OSTBC. Our future research topics will be the design of high-rate and high-diversity SM-OSTBCs when more transmit antennas are deployed.

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