High-rate Space-Time Block Coded Spatial Modulation

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***Abstract*—This paper presents high-rate Space-Time Block Coded Spatial Modulation (STBC-SM) schemes for 4 and 6 transmit antennas. In these schemes, transmit codeword matrices are divided into two separate matrices, namely, Spatial Constellation (SC) matrix and Space-Time Block Code (STBC) matrix. The introduction of SC matrix makes it convenient in the design of STBC-SM codewords and signal detection. Simulation results are provided to demonstrate BER performance and hardware complexity in comparison with the STBC-SM in [1].**

I. Introduction

The use of multiple transmit and receive antennas (i.e., MIMO systems) has been theoretically shown to significantly improve spectral efficiency of wireless communication systems [2]–[3]. Since then, numerous researchers concentrate on the development of two main MIMO transmission strategies, namely, space-time block coding (STBC) and spatial multiplexing. The aim of STBC is improve Bit Error Rate (BER) performance of a wireless system by means of transmit diversity, whereas that of spatial multiplexing is to increase spectral efficiency, and thus data rate.

One attractive method for realizing transmit diversity is to employ orthogonal space-time block coding (O-STBC) because of their full diversity and their simple decoding algorithms [4]–[5]. Unfortunately, rate-one full diversity O-STBC exists only for the case of 2 transmit antennas. The symbol rate of O-STBC is upper bounded by $3/4$ symbol per channel use for more than 2 transmit antennas [5].

In contrast to O-STBCs, spatial multiplexing is developed due to the increasing 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 [6]. In this system, independent co-channel signals are transmitted simultaneously from transmit antennas, hence creating a high level of inter-channel interference (ICI) at the receiver. This phenomenon causes the complexity of optimal maximum likelihood (ML) decoder to grow exponentially with the number of transmit antennas. 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 degradation.

In recent publication, Mesleh *et al.* introduced a novel concept called spatial modulation (SM), which enables high transmission rate without facing ICI problem [7]. 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 of multiplexing gain of multiple transmit antennas without taking the transmit diversity of MIMO systems into consideration.

Very recently, Başar *et al.* introduced Space-Time Block Coded Spatial Modulation (STBC-SM), which is designed to take advantage of SM as well as STBC [1]. 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 spectral efficiency, 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 [1]. That is, an increase of $\frac{1}{2}\log_2 c$ (bits/s/Hz) in the spectral efficiency is obtained as compared to Alamouti's scheme.

In this paper, we introduce the concept of spatial constellation (SC) codeword matrices. Similar to [1], we also use Alamouti's STBC as the core STBC. Then, the resulting STBC-SM codewords are obtained simply by multiplying SC codewords matrices with Alamouti's codewords matrices. The problem of designing STBC-SM codewords becomes that of designing SM codewords so that a diversity order of $2n_R$, where n_R is the number of received antennas, is achieved. Thanks to the concept of SC codewords, the design and the detection of STBC-SM schemes become easier. Furthermore, the increase in spectral efficiency is no longer limited to $\frac{1}{2}\log_2 c$ (bits/s/Hz) as in [1]. The more number of SC codewords we can design, the higher spectral efficiency we can get.

For the purpose of illustration, we propose two STBC-SM schemes for 4 and 6 transmit antennas. The first scheme

(4 transmit antennas) has a total of 8 SC codewords, while the second one has a total of 16 codewords. Consequently, spectral efficiency of the proposed schemes increases by 1.5 and 2 bits/s/Hz, respectively, compared to Alamouti' scheme. Whereas, an increase of 0.5 bits/s/Hz is achieved compared to STBC-SM schemes in [1] for the same number of transmit antennas. Simulation results are provided to verify BER performance of proposed STBC-SM schemes.

The rest of the paper is organized as follows. Section II presents system model and the concept of SC codewords. In section III, the proposed SC codewords for 4 and 6 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 a multiple antenna system with n_T transmit and n_R receive antennas, referred to as (n_T, n_R) system, in the presence of a quasi-static Rayleigh fading MIMO channel. With the 2×2 Alamouti's STBC codewords $\mathbf{X} \in \Omega_X$ as the core STBC, whose entries are drawn from M-QAM or M-PSK constelation Ω_M, the received $n_R \times 2$ signal matrix $\mathbf{Y}$ is given by:

$$\begin{aligned}\mathbf{Y} &= \sqrt{\gamma}\mathbf{HC} + \mathbf{N} \\ &= \sqrt{\gamma}\mathbf{HSX} + \mathbf{N} \qquad (1)\end{aligned}$$

where $\mathbf{H}$ and $\mathbf{N}$ respectively denote $n_R \times n_T$ channel matrix and $n_R \times 2$ 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 2 symbol periods and changes independently from one codeword to another. $\mathbf{C} = \mathbf{SX}$ and $\mathbf{S}$ denote $n_T \times 2$ STBC-SM codeword matrix and $n_T \times 2$ SC codeword matrix, respectively. The transmit codeword $\mathbf{C}$ is normalized such that the ensemble average of the trace of $\mathbf{C}^H\mathbf{C}$ is equal to 2, i.e., $E\{\text{tr}(\mathbf{C}^H\mathbf{C})\} = 2$. γ is the average SNR at each receive antenna.

B. Concept of Spatial Constellation

Let $\tilde{\mathbf{H}} = \mathbf{HS}$ be the $n_R \times 2$ equivalent channel matrix. Then, for different matrices $\mathbf{S}$, and for a given channel $\mathbf{H}$, we obtain different realizations of equivalent channel $\tilde{\mathbf{H}}$. This amounts to selecting different combinations of transmit antenna pair to create different equivalent channel matrices $\tilde{\mathbf{H}}$ as proposed in [1]. Therefore, besides the information bits carried by Alamouti's codewords, additional bits can be obtained by existence of matrices $\mathbf{S}$ in the signal space Ω_S. Clearly, a matrix $\mathbf{S}$ can be considered as a signal point within the signal space Ω_S. Hence, $\mathbf{S}$ and Ω_S are referred to as Spatial Constellation codewords and Spatial Constellation, respectively. Now the problem of designing STBC-SM codewords becomes that of designing SC matrices.

III. Proposed STBC-SM schemes and Signal Detection

A. Design of SC codeword matrices

As explained above, STBC-SM codewords are obtained by multiplying the SC codewords with the core STBC ones. Thus, what we have to do is to design suitable SC codewords.

Let $\mathbf{s}_k$ and $\mathbf{s}_k^*$ be 2×1 vectors of the forms

$$\mathbf{s}_k = \begin{pmatrix} e^{jk\alpha} \\ 0 \end{pmatrix} \qquad (2)$$

$$\mathbf{s}_k^* = \begin{pmatrix} 0 \\ -e^{-jk\alpha} \end{pmatrix} \qquad (3)$$

where k is some integer number and α is an angle to be determined.

The spatial constellation Ω_S for $n_T = 4$ transmit antennas consists of $K = 8$ SC codewords as follows:

$$\begin{aligned}\mathbf{S}_1 &= \begin{pmatrix} \mathbf{s}_0 & \mathbf{s}_0^* & \mathbf{0} & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_2 &= \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{s}_0 & \mathbf{s}_0^* \end{pmatrix}^T \\ \mathbf{S}_3 &= \begin{pmatrix} \mathbf{0} & \mathbf{s}_1 & \mathbf{s}_1^* & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_4 &= \begin{pmatrix} \mathbf{s}_1 & \mathbf{0} & \mathbf{0} & \mathbf{s}_1^* \end{pmatrix}^T \\ \mathbf{S}_{5:8} &= e^{j\theta}\mathbf{S}_{1:4}\end{aligned}$$

where $\mathbf{0}$ is the 2×1 zero vector; T denotes matrix transpose; θ is another angle to be determined.

Similarly, the spatial constellation Ω_S for $n_T = 6$ transmit antennas consists of the following $K = 16$ SC codewords:

$$\begin{aligned}\mathbf{S}_1 &= \begin{pmatrix} \mathbf{s}_0 & \mathbf{s}_0^* & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_2 &= \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{s}_0 & \mathbf{s}_0^* & \mathbf{0} & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_3 &= \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{s}_0 & \mathbf{s}_0^* \end{pmatrix}^T \\ \mathbf{S}_4 &= \begin{pmatrix} \mathbf{0} & \mathbf{s}_1 & \mathbf{s}_1^* & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_5 &= \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{s}_1 & \mathbf{s}_1^* & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_6 &= \begin{pmatrix} \mathbf{s}_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{s}_1^* \end{pmatrix}^T \\ \mathbf{S}_7 &= \begin{pmatrix} \mathbf{s}_2 & \mathbf{0} & \mathbf{s}_2^* & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_8 &= \begin{pmatrix} \mathbf{0} & \mathbf{s}_2 & \mathbf{0} & \mathbf{s}_2^* & \mathbf{0} & \mathbf{0} \end{pmatrix}^T \\ \mathbf{S}_{9:16} &= e^{j\theta}\mathbf{S}_{1:8}\end{aligned}$$

Based on the rank and determinant criteria [8] and using exhaustive computer search, we find the optimal values for α and θ as in Table I, where $\delta_{\min}$ is the minimum determinant given by:

$$\delta_{\min} = \min_{\mathbf{C}_k \neq \mathbf{C}_l} \det\left((\mathbf{C}_k - \mathbf{C}_l)^H(\mathbf{C}_k - \mathbf{C}_l)\right) \qquad (4)$$

where H denotes Hermitian transpose of a matrix. $\mathbf{C}_k$ and $\mathbf{C}_l$ are two different STBC-SM codewords.

B. Optimal ML Detection of the proposed STBC-SM schemes

Assuming that perfect channel state information is available at the receiver. An optimal ML decoder for the proposed STBC-SM schemes exhaustively search over all codewords $\mathbf{S}$

TABLE I
ANGLE VALUES OF SC CODEWORDS FOR DIFFERENT QAM CONSTELLATIONS

n_T	M	α	θ	$\delta_{\min}$
4	2	1.323	0.844	1.8
	4	0.963	1.318	3.99
	8	0.963	1.318	3.99
	16	0.75	1.318	3.97
6	2	0.785	1.178	1.21
	4	1.178	1.408	1.68
	8	1.178	1.36	1.04
	16	1.178	0.948	0.44

in spatial constellation Ω_S and codewords $\mathbf{X}$ in the Alamout's codeword space Ω_X and chooses the pair of matrices $(\hat{\mathbf{S}}, \hat{\mathbf{X}})$ that satisfies the following ML decoding rule:

$$(\hat{\mathbf{S}}, \hat{\mathbf{X}}) = \arg \min_{\mathbf{S}\in\Omega_S, \mathbf{X}\in\Omega_X} \|\mathbf{Y} - \sqrt{\gamma}\mathbf{HSX}\|^2 \tag{5}$$

For a given matrix $\mathbf{S}_k \in \Omega_S, k = 1, \cdots, K$, we have a corresponding $n_R \times 2$ equivalent matrix $\tilde{\mathbf{H}}_k = \mathbf{HS}_k$, then the system in (1) becomes the well-known Alamouti system:

$$\mathbf{Y} = \sqrt{\gamma}\tilde{\mathbf{H}}_k\mathbf{X} + \mathbf{N} \tag{6}$$

Equation (6) can be reorganized as [9]:

$$\mathbf{y} = \sqrt{\gamma}\mathcal{H}_k \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \mathbf{n} \tag{7}$$

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

$$\mathcal{H}_k = \begin{bmatrix} \tilde{h}_{11,k} & \tilde{h}_{12,k} \\ \tilde{h}^*_{12,k} & -\tilde{h}^*_{11,k} \\ \tilde{h}_{21,k} & \tilde{h}_{22,k} \\ \tilde{h}^*_{22,k} & -\tilde{h}^*_{21,k} \\ \vdots & \vdots \\ \tilde{h}_{n_R1,k} & \tilde{h}_{n_R2,k} \\ \tilde{h}^*_{n_R2,k} & -\tilde{h}^*_{n_R1,k} \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{1,k} & \mathbf{h}_{2,k} \end{bmatrix} \tag{8}$$

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

- For each matrix $\mathcal{H}_k$ and for each signal pair $(x_{1,m}, x_{2,m})$ in the transmit constellation, compute the following Euclidean distances:
  - $d^m_{1,k} = \left\|\mathbf{y} - \sqrt{\gamma}\mathbf{h}_{1,k}x_{1,m}\right\|^2$, for $m = 1, \cdots, M$.
  - $d^m_{2,k} = \left\|\mathbf{y} - \sqrt{\gamma}\mathbf{h}_{2,k}x_{2,m}\right\|^2$, for $m = 1, \cdots, M$.
- Find $d^{\min}_{1,k}$ among M values of $d^m_{1,k}$ and $\hat{x}^k_1$ corresponding to $d^{\min}_{1,k}$.
- Find $d^{\min}_{2,k}$ among M values of $d^m_{2,k}$ and $\hat{x}^k_2$ corresponding to $d^{\min}_{2,k}$
- Calculate $d_k = d^{\min}_{1,k} + d^{\min}_{2,k}$, 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: $\hat{\mathbf{S}} = \mathbf{S}_{\hat{k}}$, $(\hat{x}_1, \hat{x}_2) = (\hat{x}^{\hat{k}}_1, x^{\hat{k}}_2)$.

IV. PERFORMANCE EVALUATION OF THE PROPOSED STBC-SM SYSTEMS

In this section, we analyze error performance of the proposed STBC-SM schemes by evaluating their pairwise error probability (PEP) and providing an upper bound for the bit error probability.

The PEP $P(\mathbf{C}_i \to \mathbf{C}_j)$ is the probability of deciding STBC-SM matrix $\mathbf{C}_j$ given that matrix $\mathbf{C}_i$ is transmitted. The PEP, conditioned on the channel $\mathbf{H}$, is given by [8]:

$$P(\mathbf{C}_i \to \mathbf{C}_j|\mathbf{H}) = Q\left(\sqrt{\frac{\gamma}{2}d^2(\mathbf{C}_i, \mathbf{C}_j)}\right) \tag{9}$$

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 $\mathbf{C}_j$. In slow fading channel (as assumed in this paper), $d^2(\mathbf{C}_i, \mathbf{C}_j)$ is given by [8], [10]:

$$d^2(\mathbf{C}_i, \mathbf{C}_j) = \sum_{k=1}^{n_T}\sum_{l=1}^{n_R} \lambda_k|\beta_{k,l}|^2 \tag{10}$$

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 [8], $\lambda_k \geq 0$.

Using the alternative form of $Q(x)$ by Craig, we can write [10]

$$\begin{aligned} P(\mathbf{C}_i \to \mathbf{C}_j|\mathbf{H}) &= \frac{1}{\pi}\int_0^{\pi/2} \exp\left[-\frac{\gamma d^2(\mathbf{C}_i, \mathbf{C}_j)}{4\sin^2\theta}\right]d\theta \\ &= \frac{1}{\pi}\int_0^{\pi/2} \prod_{k=1}^{r}\prod_{l=1}^{n_R} \exp\left[-\frac{\gamma\lambda_k|\beta_{k,l}|^2}{4\sin^2\theta}\right]d\theta \end{aligned} \tag{11}$$

where r is the number of non-zero eigenvalues among n_T eigenvalues of $\mathbf{C}_\Delta$. Averaging (11) over the channel matrix $\mathbf{H}$, or equivalently over $|\beta_{k,l}|^2$ with chi-square distribution, we obtain the PEP as [10]:

$$P(\mathbf{C}_i \to \mathbf{C}_j) = \frac{1}{\pi}\int_0^{\pi/2} \prod_{k=1}^{r}\left[1 + \frac{\gamma\lambda_k}{4\sin^2\theta}\right]^{-n_R} d\theta \tag{12}$$

Assuming b information bits are transmitted using one of a total $N = KM^2$ STBC-SM codeword matrices $\mathbf{C}_1, \mathbf{C}_2, \cdots, \mathbf{C}_N$, i.e., $b = \log_2 N$. Then, using the PEP in (12), an upper bound for the average bit error probability (BEP) of the proposed STBC-SM systems is given by [11]:

$$P_b \leq \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{N} \frac{P(\mathbf{C}_i \to \mathbf{C}_j)w_{i,j}}{b} \tag{13}$$

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 (13) reduces to:

$$P_b \le \frac{2}{bN} \sum_{i=1}^{N-1} \sum_{j=i}^{N} P(\mathbf{C}_i \to \mathbf{C}_j) w_{i,j} \tag{14}$$

V. Simulation Results and Discussions

In this section, we use Monte Carlo simulations to verify BER performance of the proposed STBC-SM schemes and make comparisons with various existing MIMO systems. We assume the channel state information is perfectly known by the receiver.

Shown in Fig. 1 are the BER performance curves of the two proposed STBC-SM scheme with 2 and 4 receive antennas using 4-QAM and 8-QAM modulations in comparison with the upper bound given in (14). We can see from Fig. 1 that as the number of receive antenna increases, the upper bounds are getting tighter in the high SNR regions. Consequently, one can use (14) as a tool to evaluate BER performance of the proposed STBC-SM schemes when the SNR is high enough.

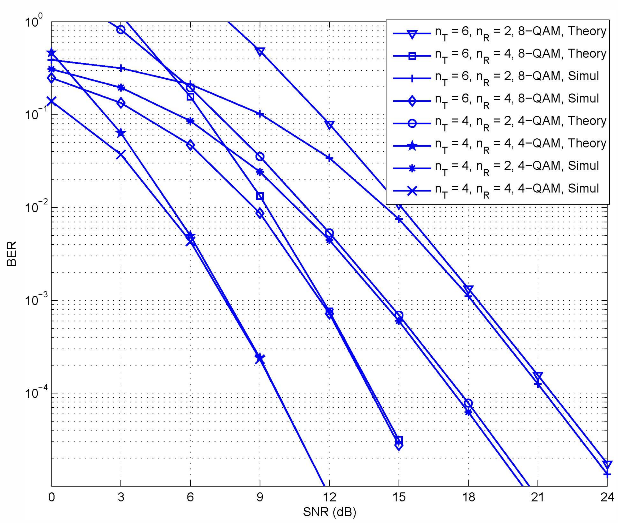

Fig. 1. Theoretical upper bounds and simulation results of BER performance of the proposed STBC-SM schemes for different numbers of receive antennas and different modulation techniques.

In Fig. 2, we compare BER performance of our proposed STBC-SM with those of Başar's STBC-SM and Orthogonal STBC (OSTBC). In the simulation, we use our proposed scheme for $n_T = 4$ transmit antennas with 8 SC codewords and 8-QAM modulation, Başar's STBC-SM for 6 transmit antennas and 8-QAM modulation, and OSTBC for 4 transmit antennas, code rate of 0.75 symbols per channel use and 64-QAM. All there systems deliver the same spectral efficiency of 4.5 bits/s/Hz. It can be seen from Fig. 2 that the proposed scheme significantly outperforms OSTBC for both $n_R = 2$ and $n_R = 4$ received antennas. Specifically, at $BER = 10^{-5}$, the proposed scheme improves approximately 5dB and 10dB in average SNR as compared to the OSTBC for $n_R = 2$ and $n_R = 4$, respectively.

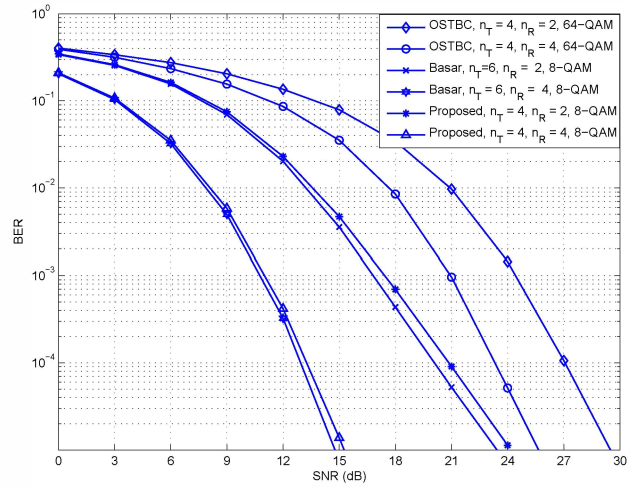

Fig. 2. BER curve of the proposed STBC-SM in comparison with those of Başar's STBC-SM, Orthogonal STBC; 4.5 bits/s/Hz.

Fig. 3 illustrates BER performances of the proposed STBC-SM, Başar's STBC-SM, VBLAST, and Alamouti's schemes. The proposed scheme uses 6 transmit antennas, 16 SC codewords and 4-QAM modulation. The Başar's STBC-SMs are with 4 transmit antennas and 8-QAM, and 8 transmit antennas and 4-QAM modulated symbols. The VBLAST utilizes 4 transmit antennas with BPSK modulation. The signal detection in the VBLAST system is maximum likelihood based on the QMLD decoder [12]. All 5 system are equipped with $n_R = 4$ receive antennas and have a spectral efficiency of 4 bits/s/Hz.

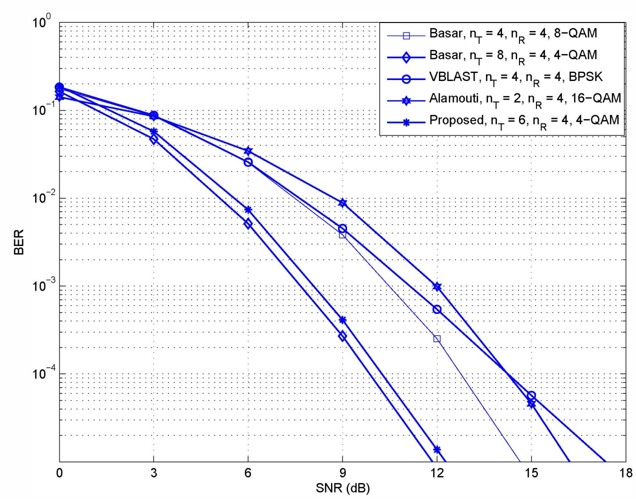

Fig. 3. BER curve of the proposed STBC-SM in comparison with those of Başar's STBC-SM, VBLAST, and Alamouti's STBC; 4 bits/s/Hz.

Simulation results clearly proves that our proposed scheme provides higher BER performance than Başar's STBC-SM with $n_T = 4$, VBLAST, and Alamouti's schemes. At $BER = 10^{-5}$, the proposed system gains about 2.5dB, 4dB and 5dB in SNR compared to Başar's STBC-SM with $n_T = 4$, Alamouti's and VBLAST schemes, respectively.

As presented above, the proposed schemes with $n_T = 4$ and $n_T = 6$ have the corresponding spectral efficiencies of $(1.5 + \log_2 M)$ and $(2 + \log_2 M)$ bits/s/Hz. Clearly, the proposed schemes can save 2 transmit antennas, i.e., lower hardware complexity, while delivering the same spectral efficiencies as do Başar's STBC-SMs with $n_T = 6$ and $n_T = 8$ [1], respectively. However, from both Fig. 2 and Fig. 3, we can see that, the smaller number of transmit antennas is achieved at the cost of insignificant degradation in BER performance.

VI. Conclusion

In this paper, we have introduced the concept of spatial constellation and spatial constellation codewords. Using this concept, the problem of designing a STBC-SM scheme becomes that of designing a spatial constellation containing a number of SC codewords. By combining the SC codewords with Alamouti's codewords, we are able to have a STBC-SM system with a diversity order of $2n_R$ and with an increase in spectral efficiency. The additional spectral efficiency is determined by the number of SC codewords we can design.

For the purpose of illustrating the concept, we proposed two STBC-SM schemes with two SC constellations for $n_T = 4$ and $n_T = 6$. It has been shown via computer simulations and theoretical upper bounds that the proposed STBC-SM offers significant improvements in BER performance compared to rate $3/4$ OSTBC, Alamouti's and VBLAST systems. In addition, the proposed schemes allows us to save a number of transmit antennas while maintaining the same spectral efficiency, yet at the cost of small degradation in BER performance. In the future work, we will concentrate on designing new SC constellations to improve spectral efficiencies and BER performance as well.

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