Diagonal Space Time Block Coded Spatial Modulation

Invited article

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Communication: received 27 October 2018, revised 24 December 2018, accepted 26 December 2018
Online early access: 28 February 2019, Digital Object Identifier: 10.32913/mic-ict-research.v2019.n1.832
The Area Editor coordinating the review of this article and deciding to accept it was Dr. Truong Trung Kien

Abstract: In this paper, a new Spatial Modulation (SM) scheme, called Diagonal Space Time Coded Spatial Modulation (DS-SM), is designed by embedding the Diagonal Space Time Code in SM. The DS-SM scheme still inherits advantages of SM while enjoying further benefits from spatial constellation (SC) designs. Based on rank and determinant criteria, a new set of four SC codewords is proposed for the DS-SM system with four transmit antennas to achieve the fourth-order diversity. Then a general design procedure for an even number of transmit antennas, larger than four, is developed by cyclically shifting two rows of the SC codewords. Simulation results show that DS-SM surpasses several existing SM schemes at the same spectral efficiency and antenna configuration. DS-SM also exhibits better performance than the benchmark systems under spatially correlated channels. The complexity of DS-SM is also analyzed and compared to other SM schemes.

Keywords: *Multiple-input multiple-output (MIMO), space time block code, spatial modulation.*

I. Introduction

Spatial Modulation (SM), proposed by Mesleh *et al.* in [1], is a new transmission technique which can overcome many drawbacks of the conventional Multiple-Input Multiple-Output (MIMO) system. Different from the previous MIMO transmission schemes such as Vertical Bell-Labs Layered Space-Time (V-BLAST) or Space-Time Block Codes (STBC), the SM system activates only one transmit antenna during a time slot to transmit a modulated symbol. Thus, SM can avoid Inter-Channel Interference (ICI) among transmitted streams and does not require strict transmit antenna synchronization. Moreover, as only one radio frequency (RF) chain is used, SM is more advantageous than the other MIMO schemes in terms of energy saving. But the most important advantage of SM is that the spectral efficiency is increased as the antenna indices are utilized to convey information bits. However, SM lacks transmit diversity and multiple receive antennas are needed at the SM receivers to attenuate the fading effect.

Various efforts have been made to cope with the problem of channel fading and improve SM performance (see [2] and the references therein). Among these works only some solutions can help SM to increase its transmit diversity. In [3], the authors proposed the so-called Coherent Space Time Shift Keying (CSTSK) which achieves the second order transmit diversity. The Time-Orthogonal-Signal-Design Assisted Space Shift Keying (TOSD-SSK) proposed in [4] can also obtain the same diversity order of CSTSK by using shaping filters at the transmitter. In [5], Basar *et al.* proposed the so-called Space Time Block Coded Spatial Modulation (STBC-SM) by combining STBC and SM. By exploiting the orthogonal structure of the Alamouti STBC the STBC-SM scheme also achieve the second-order transmit diversity with low-complexity maximum-likelihood detection.

In [6], Le *et al.* introduced the concept of Spatial Constellation (SC) and proposed a high-rate Space-Time Block Coded Spatial Modulation (STBC-SM) scheme for four and six transmit antennas. This STBC-SM scheme has higher spectral efficiency than STBC-SM in [5] thanks to the increased number of spatial constellation matrices. In [7], based on cyclic structure and complex constellation rotation another SM scheme, abbreviated as STBC-CSM, was proposed to further improve the spectral efficiency of STBC-SM while still maintaining the second-order transmit diversity. In [8], an improved SM scheme called Spatially Modulated Orthogonal Space Time Block Coding (SM-OSTBC) was proposed. This scheme attains the maximum spectral efficiency of $(n_T - 2 + \log_2 M)$ bit per channel

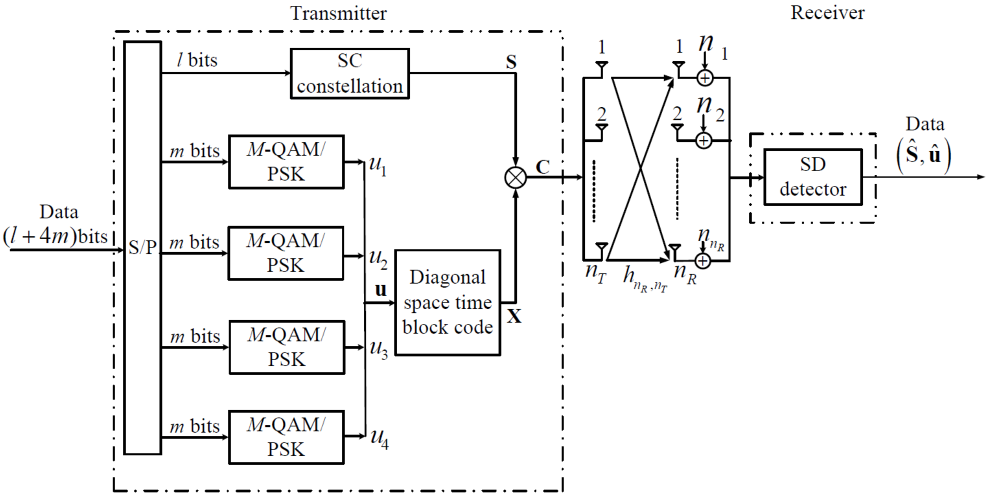

Figure 1. Block diagram of the DS-SM scheme.

use (bpcu) when the number of active antennas is equal the number of transmit antennas, i.e., $n_A = n_T$, where M is the modulation order. However, SM-OSTBC has a limitation that it is only applicable to the systems equipped with an even number of transmit antennas greater than or equal to four. To overcome this drawback, Wang *et al.* [9] proposed the so-called Spatially Modulated Diagonal Space Time Code (SM-DC) that can apply to the systems with the number of transmit antennas equal to or less than four. The SM-DC scheme also achieves the second-order transmit diversity.

The objective of the current paper is to improve the SM performance by increasing its transmit diversity order. Inspired by the concept of the SC matrices in [6] and the Diagonal STBC in [9], we propose an enhanced SM scheme by designing a new set of SC matrices and incorporating them with a Diagonal Space Time Block Code. The proposed scheme is referred to as DS-SM. Compared to SM-DC, the DS-SM scheme has the following advantages. First, our proposed DS-SM can apply to MIMO systems with an even number of transmit antennas greater than or equal to four. Second, we propose to use an optimal linear matrix to maximize the minimum product distance between any two points of the signal constellation. Finally, our scheme achieves the fourth-order transmit diversity in contrast to the second order by SM-DC.

Our contributions in this paper are as follows.

1) A new set of four SC codewords is proposed for the DS-SM system equipped with four transmit antennas to achieve the fourth-order transmit diversity.
2) A general procedure to design extended SC codewords is formulated for the DS-SM systems with an even number of transmit antennas greater than four.
3) The proposed scheme requires only one RF transmit chain, therefore eliminating the ICI effect and facilitating the IAS requirement.
4) Theoretical upper bound of the bit error probability (BEP) of the proposed scheme is derived to verify simulation results. The proposed scheme is demonstrated to surpass the related SM-based MIMO ones including SM-DC, STBC-SM, and STBC-CSM in both uncorrelated and correlated fading environments for the same antenna configuration and spectral efficiency.

The remainder of this paper is organized as follows. Section II presents the system model of the proposed DS-SM scheme. Section III describes the SC codeword design followed by the signal detection introduced in Section IV. Performance evaluation is presented in Section V, and finally conclusions are drawn in Section VI.

Notation: The following mathematical notations are used throughout the paper. $(\cdot)^T$ and $(\cdot)^H$ denote vector/matrix transpose and conjugate transpose, respectively. $\Re(\cdot)$ and $\Im(\cdot)$ denote the real and the imaginary part of a complex number, respectively. $\text{vec}(\mathbf{A})$ denotes the column-vectorial stacking operation of matrix $\mathbf{A}$. $\text{diag}(\mathbf{x})$ denotes a diagonal matrix built from vector $\mathbf{x}$.

II. System Model

Figure 1 illustrates the block diagram of the proposed SM scheme with $n_T = 4$ transmit antennas and n_R receive antennas. It is assumed that data bits arrive at the transmitter in blocks each of which consists of $(l + 4m)$ bits. The first l bits are mapped into a 4×4 SC matrix out of $K = 2^l$ SC matrices in the spatial constellation Ω_S. The remaining $4m$ bits are modulated by M-QAM/PSK modulators, where $M = 2^m$, to make a 4×1 modulated symbol vector

$\mathbf{u} = \begin{bmatrix} u_1 & u_2 & u_3 & u_4 \end{bmatrix}^T$. Using DSTBC, $\mathbf{u}$ is linearly combined with a rotation matrix $\mathbf{W}$ as follows:

$$\tilde{\mathbf{u}} = \mathbf{W}[\Re(\mathbf{u}), \Im(\mathbf{u})]^T. \quad (1)$$

The multidimensional rotation matrix $\mathbf{W}$ [10] for maximizing the minimum product distance between any two points of the signal constellation is given as

$$\mathbf{W} = \sqrt{\frac{2}{n}} \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix}, \quad (2)$$

where $w_{tk} = \cos\left(\frac{\pi}{4n}(4t-1)(2k-1)\right)$, for $1 \le t,\ k \le n$, $n = 2n_T = 8$, and $\sqrt{2/n}$ is used to normalize $\mathbf{W}$.

Then, the elements of the rotated signal vector $\tilde{\mathbf{u}}$ are rearranged to obtain the following vector

$$\tilde{\mathbf{x}} = \begin{bmatrix} \tilde{u}_1 + j\tilde{u}_5 & \tilde{u}_2 + j\tilde{u}_6 & \tilde{u}_3 + j\tilde{u}_7 & \tilde{u}_4 + j\tilde{u}_8 \end{bmatrix}^T. \quad (3)$$

The 4×4 diagonal STBC matrix is then obtained as $\mathbf{X} = \mathrm{diag}(\tilde{\mathbf{x}})$. Finally, the 4×4 transmitted codeword $\mathbf{C}$ is created simply by multiplying $\mathbf{S}$ by $\mathbf{X}$, i.e., $\mathbf{C} = \mathbf{SX}$. This resulted codeword $\mathbf{C}$ will be transmitted from four transmit antennas within $T = 4$ periods.

Under the assumption that the channel is quasi-static and flat fading, the $n_R \times 4$ received signal matrix $\mathbf{Y}$ at the receiver is given by

$$\mathbf{Y} = \sqrt{\frac{\gamma}{E_s}}\mathbf{HC} + \mathbf{N} = \sqrt{\frac{\gamma}{E_s}}\mathbf{HSX} + \mathbf{N}, \quad (4)$$

where γ is the average signal-to-noise ratio (SNR) at each receive antenna. E_s is the average energy of the M-QAM/PSK modulated symbols, $\mathbf{H}$ and $\mathbf{N}$ respectively denote an $n_R \times 4$ channel matrix and an $n_R \times 4$ noise matrix whose entries are assumed to be independent and identically distributed (i.i.d.) random variables with zero mean and unit variance.

III. SC CODEWORD DESIGN

1. Basic SC Codewords for Four Transmit Antennas

As seen in Figure 1, a part of data bits are conveyed by SC codewords, so these codewords should be carefully designed. Based on the SC concept [6], a basic set of four SC codewords is proposed as follows:

$$\mathbf{S}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5a)$$

$$\mathbf{S}_2 = \begin{bmatrix} 0 & e^{j\theta} & 0 & 0 \\ 0 & 0 & e^{j\theta} & 0 \\ 0 & 0 & 0 & e^{j\theta} \\ j & 0 & 0 & 0 \end{bmatrix}, \quad (5b)$$

$$\mathbf{S}_3 = \mathbf{S}_2^2, \quad (5c)$$

$$\mathbf{S}_4 = \mathbf{S}_2^3. \quad (5d)$$

Using the rank and determinant criteria [11], the rotation angle θ is optimized to attain full diversity and maximum coding gain. Particularly, an exhaustive search is applied to find the optimal value of the angle $\theta \in [0, \pi/2]$ that maximizes the coding gain distance (CGD) $\delta_{\min}(\theta)$ as follows:

$$\delta_{\min} = \min_{\mathbf{C} \neq \mathbf{C}'} \det(\mathbf{C} - \mathbf{C}')^H (\mathbf{C} - \mathbf{C}'), \quad (6)$$

$$\theta_o = \arg\max_{\theta} \delta_{\min}(\theta). \quad (7)$$

Table I presents the resulted optimal angle θ_o and CGD for different modulation techniques. The spectral efficiency of DS-SM equipped with four transmit antennas is given by

$$C_{\mathrm{DS-SM}} = \frac{1}{4}\left(\log_2 4 + \log_2 M^4\right) = \frac{1}{2} + \log_2 M\ (\mathrm{bpcu}). \quad (8)$$

2. SC Codeword Design for an Even Number of Transmit Antennas

Based on the above basic set of SC codewords for four antennas, an extended set of SC codewords are constructed for DS-SM with even number of transmit antennas. For illustration purpose, a DS-SM system for six transmit antennas is considered. From the first SC codeword $\mathbf{S}^1 = \begin{bmatrix} \mathbf{s}_{1,1} & \mathbf{s}_{1,2} \end{bmatrix}^T$, adding a 2×4 zero matrix below the columns of the $\mathbf{S}^1$ matrix, three SC codewords are generated by cyclically shifting two rows of the new matrix as follows:

$$\mathbf{S}_1^1 = \begin{bmatrix} \mathbf{s}_{1,1} \\ \mathbf{s}_{1,2} \\ \mathbf{0} \end{bmatrix}, \quad \mathbf{S}_2^1 = \begin{bmatrix} \mathbf{0} \\ \mathbf{s}_{1,1} \\ \mathbf{s}_{1,2} \end{bmatrix}, \quad \mathbf{S}_3^1 = \begin{bmatrix} \mathbf{s}_{1,2} \\ \mathbf{0} \\ \mathbf{s}_{1,1} \end{bmatrix}. \quad (9)$$

TABLE I
OPTIMAL VALUES OF θ AND CORRESPONDING CGDS FOR THE BASIC SC CODEWORDS

Modulation	BPSK	4QAM	8QAM	16QAM
θ	0.52	1.36	0.2	0.4
$\delta_{\min}$	0.11	0.037	3.6×10^{-3}	7×10^{-4}

When the number of transmit antennas is even and greater than four, the number of SC matrices increase to $2n_T$. As a result, the number of data bits conveyed by the SC matrices are $\lfloor \log_2(2n_T) \rfloor$ bits while the number of data bits carried by modulated signals are $4m$ bits ($M = 2^m$). Therefore, the spectral efficiency of DS-SM is given by

$$\begin{aligned} C_{\text{DS-SM}} &= \frac{4m + \lfloor \log_2(2n_T) \rfloor}{T} \\ &= m + \frac{\lfloor \log_2(2n_T) \rfloor}{4} \text{ (bpcu)}. \end{aligned} \quad (10)$$

Comparing to SM-DC in [9] which has the spectral efficiency of $\log_2 M_1 + 2\log_2 M$ over $T = 2$ symbol periods resulting in the actual spectral efficiency of $\frac{\log_2 M_1}{2} + m$, DS-SM can become competitive in the systems with large number of transmit antennas and small modulation size. Note that the spectral efficiency of SM-DC does not depend on the number of transmit antennas n_T but the modulation order M_1 of the symbols in the spatial codewords. Thus, SM-DC can easily achieve higher spectral efficiency than DS-SM when the number of transmit antennas is small, e.g. $n_T < 4$, by increasing M_1. However, this increase is more vulnerable to spatial codeword errors, which sacrifices BER performance of SM-DC as demonstrated by simulation results in the later section.

In summary, a general procedure to design the SC codeword for a DS-SM system with an even number of transmit antennas is given as follows:

1) For a given number of even transmit antennas n_T and an arbitrary level of modulation M, using Table I to choose the suitable value of θ and generate the basic set of four SC codewords.
2) Adding an $(n_T - 4) \times 4$ zero matrix under the columns of the basic SC codewords and cyclically shifting two rows of these matrices to increase the number of SC codewords to $2n_T$.
3) Generating a new set of the SC codewords as $\mathbf{S}_k$, for all $k = 1, 2, \ldots, \lfloor \log_2(2n_T) \rfloor$.

IV. Signal Detection

For a given matrix $\mathbf{S}_k$, $k = 1, 2, \ldots, K$, we can construct the $n_R \times 4$ equivalent matrix $\tilde{\mathbf{H}}_k = \sqrt{\gamma / E_s}\mathbf{H}\mathbf{S}_k$. Therefore, the system equation in (4) can be re-written as

$$\mathbf{Y} = \tilde{\mathbf{H}}_k \mathbf{X} + \mathbf{N}. \quad (11)$$

Based on the diagonal structure of $\mathbf{X}$, Equation (11) can be represented as follows:

$$\mathbf{y} = \mathbf{H}_{e,k}\tilde{\mathbf{x}} + \mathbf{n}, \quad (12)$$

where $\mathbf{H}_{e,k} = \left[\text{diag}\left(\tilde{\mathbf{h}}_1\right), \ldots, \text{diag}\left(\tilde{\mathbf{h}}_{n_R}\right)\right]^T$, $\tilde{\mathbf{h}}_k$ is the k-row of $\tilde{\mathbf{H}}_k$, $k = 1, 2, \ldots, n_R$, $\mathbf{y} = \text{vec}\left(\mathbf{Y}^T\right)$, and $\mathbf{n} = \text{vec}\left(\mathbf{N}^T\right)$. Converting equation (12) into the equivalent real system-equation and using (1) and (4), we have

$$\mathbf{v} = \mathbf{M}_k \mathbf{s} + \mathbf{w}, \quad (13)$$

where

$$\begin{aligned} \mathbf{s} &= \left[\Re(\mathbf{u}) \quad \Im(\mathbf{u})\right]^T, \\ \mathbf{w} &= \left[\Re(\mathbf{n}) \quad \Im(\mathbf{n})\right]^T, \\ \mathbf{v} &= \left[\Re(\mathbf{y}) \quad \Im(\mathbf{y})\right]^T, \\ \mathbf{M}_k &= \begin{bmatrix} \Re\left(\mathbf{H}_{e,k}\right) & -\Im\left(\mathbf{H}_{e,k}\right) \\ \Im\left(\mathbf{H}_{e,k}\right) & \Re\left(\mathbf{H}_{e,k}\right) \end{bmatrix} \mathbf{W}. \end{aligned}$$

The system equation in (13) is similar to that of a conventional spatial multiplexing scheme. Therefore, a Sphere Decoder (SD) in [12, 13] can be used to detect $\mathbf{s}$, as follows:

$$(\hat{\mathbf{s}})_k = \arg\min_{\mathbf{s}} \|\mathbf{t}_k - \mathbf{R}_k \mathbf{s}\|^2, \quad (14)$$

where $\mathbf{t}_q = \mathbf{Q}_k^H \mathbf{v}$, $\mathbf{Q}_k$ and $\mathbf{R}_k$ are the resulting matrices from the QR decomposition of $\mathbf{M}_k$, i.e., $\mathbf{M}_k = \mathbf{Q}_k \mathbf{R}_k$.

The index k of the transmitted SC codeword is then determined as [8]

$$\hat{k} = \arg\min_k \|\mathbf{t}_k - \mathbf{R}_k (\hat{\mathbf{s}})_k\|^2 + \mathbf{v}^H \mathbf{v} - \mathbf{t}_k^H \mathbf{t}_k. \quad (15)$$

Finally, the transmitted information bits are recovered from a pair of the detected SC codeword and the detected signal vector $(\hat{\mathbf{S}}_{\mathbf{k}}, \hat{\mathbf{u}}_{\mathbf{k}})$ at the receiver.

1. Complexity Analysis

In this section, computational complexity for signal processing at the DS-SM receivers is analyzed and compared with related SM-based MIMO schemes using SD [12, 13]. It is assumed that each real arithmetic calculation accounts for a floating point operation (flop). Therefore, a complex addition or subtraction requires two flops while a complex multiplication requires six operations including four real multiplications and two real additions. We also assume that the channel remains unchanged within T-symbol periods.

In the pre-processing state, the complexity of computing $\tilde{\mathbf{H}}_k$ in (11), $\mathbf{M}_k$ in (13), QR decomposition of $\mathbf{M}_k$ in (13) and a signal vector $\mathbf{t}_k, k = 1, 2, \ldots, K$, in (15) is given as

$$\begin{aligned} \Delta_{\text{pre}} = &\frac{4}{T}\left(2048 n_R + 3n_T^2 n_R + 6 n_R n_T - 34\right) K \\ &+ (143 n_R + 7) K. \end{aligned} \quad (16)$$

Therefore, the complexity of DS-SM is given by

$$\Delta = \frac{\Delta_{\text{pre}} + \Delta_S}{4m + 2}, \quad (17)$$

where Δ_S is the average number of operations used in the SD searching stage.

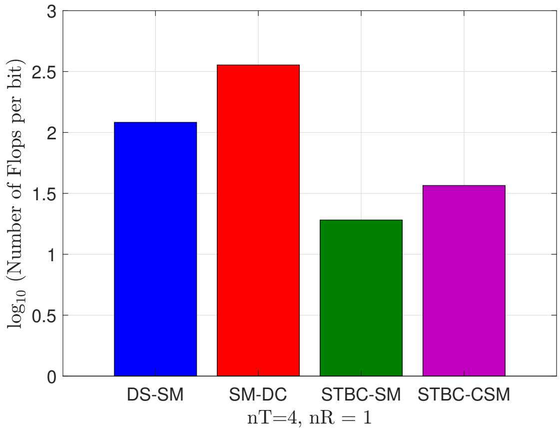

Figure 2. Complexity comparison of DS-SM, SM-DC, STBC-SM, STBC-CSM at the spectral efficiency 3.5 bpcu, SNR 9 dB, 4 transmit antennas, 1 receive antenna, $T = 80$ symbol periods.

Figure 2 compares the detection complexity of the DS-SM to the related SM schemes such as SM-DC, STBC-SM, and STBC-CSM, in a MIMO scheme with $n_T = 4$, $n_R = 1$, and at a spectral efficiency of 3.5 bpcu. It can be seen that the complexity of DS-SM is larger than those of STBC-SM and STBC-CSM but lower than that of SM-DC.

2. Theoretical Upper Bound for BEP

Based on the pairwise error probability (PEP), the upper bound of BEP for the DS-SM scheme can be derived. By definition, PEP, denoted by $P(\mathbf{C}_i \rightarrow \mathbf{C}_j)$, is the probability that a matrix $\mathbf{C}_i$ is transmitted while the receiver mistakenly decides it by another matrix $\mathbf{C}_j$. The upper bound of PEP is given by [14]

$$P_b \leq \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{P(\mathbf{C}_i \rightarrow \mathbf{C}_j) w_{i,j}}{\log_2 N}, \tag{18}$$

where $N = KM^4$ and $w_{i,j}$ is the number of bits in error between the matrices $\mathbf{C}_i$ and $\mathbf{C}_j$.

The conditional PEP of the DS-SM system is given by

$$P\left(\mathbf{C}_i \rightarrow \mathbf{C}_j | \mathbf{H}\right) = Q\left(\sqrt{\frac{\gamma}{2} d^2\left(\mathbf{C}_i, \mathbf{C}_j\right)}\right), \tag{19}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-y^2/2} dy$. From [15], PEP is given by

$$P(\mathbf{C}_i \rightarrow \mathbf{C}_j) = \frac{1}{\pi} \int_0^{\pi} \left[\left(\frac{1}{1 + \frac{\gamma \lambda_{i,j,1}}{4\sin^2\phi}} \right)^{n_R} \left(\frac{1}{1 + \frac{\gamma \lambda_{i,j,2}}{4\sin^2\phi}} \right)^{n_R} \times \left(\frac{1}{1 + \frac{\gamma \lambda_{i,j,3}}{4\sin^2\phi}} \right)^{n_R} \left(\frac{1}{1 + \frac{\gamma \lambda_{i,j,4}}{4\sin^2\phi}} \right)^{n_R} \right] d\phi. \tag{20}$$

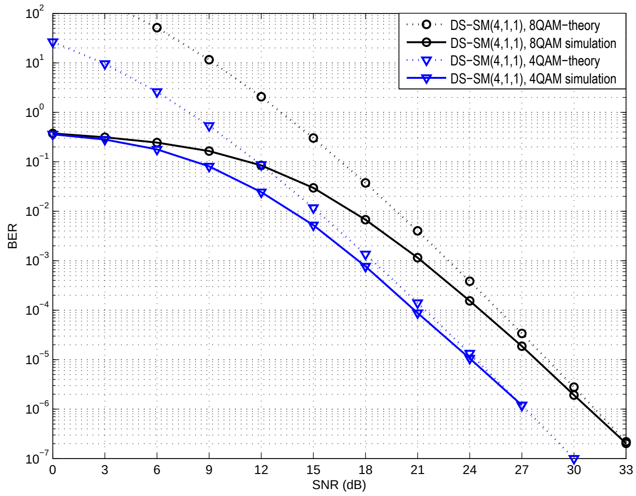

Figure 3. Simulated average BER and theoretical BEP of DS-SM.

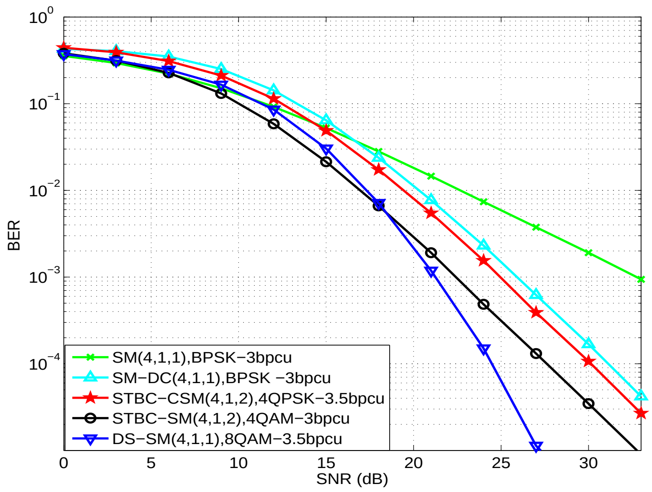

Figure 4. BER performance of DS-SM, SM, STC-SM, SM-DC, and STBC-CSM when $n_R = 1$ and spectral efficiency is 3 bpcu.

V. Simulation Results

In this section, performance of the proposed SM is evaluated and compared with several existing SM systems such as SM, SM-DC, STBC-SM and STBC-CSM for the case using different modulation techniques. The MIMO configuration with number of transmit antennas n_T, receive antennas n_R, and active antennas n_A in each scheme is denoted by (n_T, n_R, n_A). Furthermore, it is assumed that all schemes employ SD for signal detection.

1. Performance Evaluation Under Uncorrelated Channel

Figure 3 illustrates the BER obtained using the theoretical analysis and simulations for DS-SM in a DS-SM$(4, 1, 1)$ system. Two modulation schemes, i.e. 4-QAM and 8-QAM,

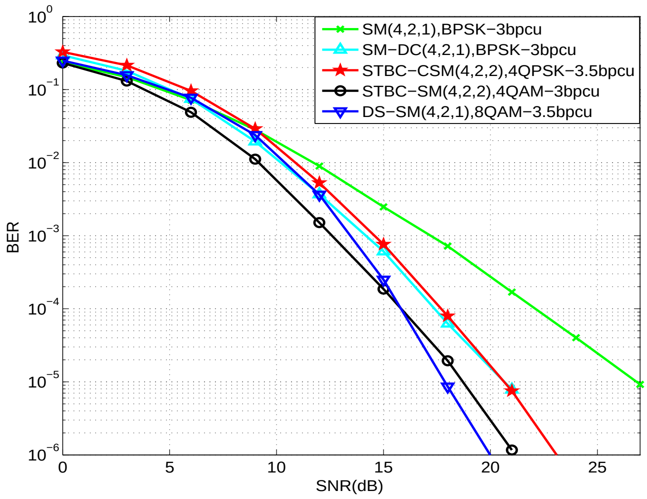

Figure 5. BER performance of DS-SM, SM, STC-SM, SM-DC, and STBC-CSM when $n_R = 2$ and spectral efficiency is 3 bpcu.

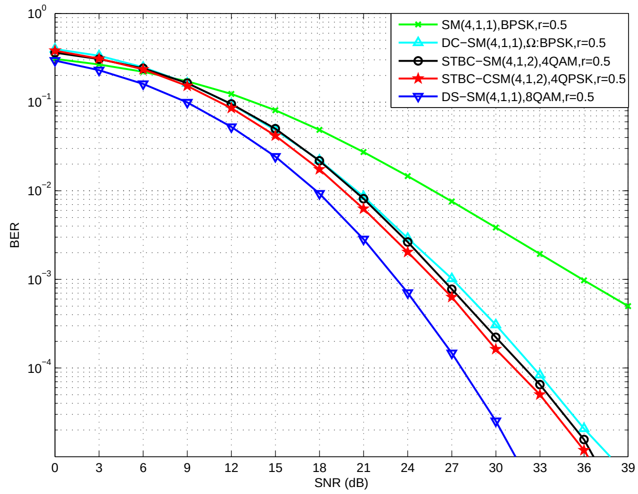

Figure 6. BER performance of DS-SM, SM, SM-DC, STBC-SM, STBC-CSM (4,1,1) at spectral efficiency of 3 bpcu and $r = 0.5$.

are used for evaluation. Note from the figure that simulation and analytical results are coincident at the high SNR region, validating the tightness of our analytical results.

Figures 4 and 5 compare performance of DS-SM$(4, n_R, 1)$ to SM$(4, n_R, 1)$, SM-DC$(4, n_R, 1)$, STBC-SM$(4, n_R, 2)$, and STBC-CSM$(4, n_R, 2)$, when being equipped with $n_R = 1$ and $n_R = 2$ receive antennas. It can be seen that DS-SM outperforms the existing schemes at high SNR region. Specifically, in Figure 4 at BER = 10^{-3}, DS-SM achieves SNR gains of 1.1 dB, 2.7 dB, 4.7 dB, and 11.5 dB compared with STBC-SM, STBC-CSM, SM-DC, and SM, respectively. These gaps become smaller in Figure 5 as all the curves have deeper slopes. At the BER of 10^{-5}, DS-SM provides SNR gains of 0.8 dB, 2.5 dB, and 18 dB over STBC-SM, STBC-CSM, and SM-DC, and SM, respectively. At low SNR region, DS-SM exhibits small degradation in SNR gain compared with STBC-SM. However, it is worth mentioning that DS-SM still has 0.5 bpcu higher spectral efficiency and requires one less RF chain compared with STBC-SM.

2. Performance Evaluation Under Spatially Correlated Channel

In order to evaluate performance of DS-SM under spatially correlated channels we use a modified channel matrix with spatial correlation effect, which is given by [16]

$$\bar{\mathbf{H}} = \mathbf{R}_R^{1/2}\mathbf{H}\mathbf{R}_T^{1/2}. \quad (21)$$

where $(n_T \times n_T)\,\mathbf{R}_T$ and $(n_R \times n_R)\,\mathbf{R}_R$ are the transmit and receive spatial correlation matrix, respectively. Each element of these matrices is generated using the exponential correlation matrix model [17], $r_{ij} = r_{ji}^*$ for $i \leq j$ where r is the correlation coefficient of the neighboring transmit and receive antennas. This is an appropriate and common model to evaluate performance of MIMO systems under the effect of spatial correlation at both transmitter and receiver.

Figure 6 illustrates the BER performance of DS-SM versus those of SM, SM-DC, STBC-SM, and STBC-CSM, all equipped with 1 transmit and 1 receive antenna. The spectral efficiency of all schemes is 3 bpcu and the correlation coefficient is $r = 0.5$. It can be seen from the figure that DS-SM is more robust than all other schemes under spatial correlation effect. For example, at BER = 10^{-3}, DS-SM offers about 2.5 dB, 3 dB, 3.7 dB, and 12 dB SNR gain over STBC-CSM, STBC-SM, SM-DC, and SM, respectively.

VI. Conclusions

In this paper, we have proposed a new MIMO scheme, called DS-SM, by embedding the Diagonal STBC into the SM system and using the rank and determinant criteria to optimize its spatial codewords. The proposed DS-SM scheme still inherits promising benefits of SM including ICI avoidance and elimination of IAS while enjoying full diversity provided by STBC. It achieves significant performance improvement over the existing SM schemes including SM, STBC-SM, SM-DC, and STBC-CSM, especially at high SNR region due to higher diversity gain, at the cost of small additional complexity. Particularly, the proposed DS-SM scheme is more robust than the benchmark schemes under the spatially correlated fading channels.

Acknowledgement

This work is sponsored by National Foundation for Science and Technology Development (NAFOSTED) under project number 102.02-2015.23.

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