Space-Time Block Coding for Spatial Modulation

Ertuğrul Başar[†], Ümit Aygölü[†], Erdal Panayırcı[‡] and H. Vincent Poor[*]

[†]Istanbul Technical University, Faculty of Electrical & Electronics Engineering, 34469, Maslak, Istanbul, Turkey
[‡]Kadir Has University, Department of Electronics Engineering, 34083, Cibali, Istanbul, Turkey
[*]Department of Electrical Engineering, Princeton University, Princeton, NJ, 08544, USA

[†]{basarer,aygolu}@itu.edu.tr, [‡]eepanay@khas.edu.tr, [*]poor@princeton.edu

Abstract—**Space-time block coded spatial modulation (STBC-SM), which employs space-time block coding (STBC) for spatial modulation (SM), is proposed as a new multiple-input multiple-output (MIMO) transmission scheme. In the STBC-SM scheme, the transmitted information symbols are expanded not only to the space and time domains but also to the spatial (antenna) domain, therefore both core STBC and antenna indices carry information. A general framework is presented for the design of the STBC-SM scheme for any number of transmit antennas. The proposed scheme is optimized by deriving its diversity and coding gains to exploit the diversity advantage of STBC. A low-complexity maximum likelihood (ML) decoder is given for the new scheme. It is shown by computer simulations that STBC-SM provides approximately 3-5 dB (depending on the spectral efficiency) better error performance than SM and V-BLAST systems.**

Keywords - Maximum likelihood decoding; MIMO systems; space-time block codes/coding; spatial modulation.

I. INTRODUCTION

A novel concept known as spatial modulation (SM) has been introduced in [1,2] as an alternative to the V-BLAST (Vertical-Bell Lab Layered Space-Time) scheme [3]. The basic idea of SM is an extension of two dimensional signal constellations (such as M-ary phase-shift keying (M-PSK), M-ary quadrature amplitude modulation (M-QAM), where M is the constellation size) to a third dimension, which is the spatial (antenna) dimension. Therefore, the information is conveyed by both amplitude/phase modulation (APM) techniques and antenna indices. It has been shown in [4] that the error performance of the SM scheme [1] can be greatly improved by the use of an optimal detector and that SM provides better error performance than V-BLAST. A space shift keying (SSK) modulation scheme has been introduced for multiple-input multiple output (MIMO) channels in [5], in which APM is eliminated and only antenna indices are used to transmit information to obtain further simplification in system design and reduction in decoding complexity. However, SSK modulation does not provide any performance advantage compared to SM. In both of the SM and SSK modulation systems, only one transmit antenna is active during each transmission interval, and therefore inter-channel interference (ICI) is totally eliminated. Despite the fact that both the SM and SSK modulation systems have been concerned with exploiting the multiplexing gain of multiple transmit antennas, the potential of the transmit diversity of MIMO systems is not explored by these two systems. This motivates the introduction in this paper of *Space-Time Block Coded Spatial Modulation (STBC-SM)*, designed for taking advantage of both SM and STBC.

In particular, in this paper, a new MIMO transmission scheme, called STBC-SM, is proposed, in which information is conveyed with an STBC matrix that is transmitted from combinations of the transmit antennas of the corresponding MIMO system. The Alamouti code [6] is chosen as the target STBC to exploit. As a source of information, we consider not only the two complex information symbols embedded in Alamouti's STBC, but also the indices (positions) of the two transmit antennas employed for the transmission of the Alamouti's STBC. A general framework is presented to construct the STBC-SM scheme for any number of transmit antennas. By considering the general STBC performance criteria [7], diversity and coding gain analyses are performed for the STBC-SM scheme to benefit the second order transmit diversity advantage of the Alamouti code. A low complexity maximum likelihood (ML) decoder is derived for the proposed STBC-SM system, to decide on the transmitted symbols as well as on the indices of the two transmit antennas that are used in the STBC transmission. It is shown by computer simulations that the proposed STBC-SM scheme has significant performance advantages over the SM with optimal decoding and over V-BLAST, due to its diversity advantage.

The organization of the paper is as follows. In Section II, we introduce our STBC-SM transmission scheme via an example with four transmit antennas, give a general STBC-SM design algorithm for n_T transmit antennas, and formulate the optimal STBC-SM ML detector. Simulation results and performance comparisons are presented in Section III. Finally, Section IV includes the main results and conclusions of the paper.

Notation: Bold lowercase and capital letters are used for column vectors and matrices, respectively. $(.)^*$ and $(.)^H$ denote complex conjugation and Hermitian transposition, respectively. For a complex variable x, $\mathrm{Re}\{x\}$ denotes the real part of x. $\mathbf{0}_{(m\times n)}$ denotes the $m \times n$ matrix with all-zero elements. $\|\cdot\|$ and $\det(\cdot)$ stand for the Frobenius norm and determinant of a matrix, respectively. The union of sets A_1 through A_n is written as $\cup_{i=1}^{n} A_i$. We use $\binom{n}{k}$, $\lfloor x \rfloor$ and $\lceil x \rceil$ for the binomial coefficient, the largest integer less than or equal to x, and the smallest integer larger than or equal to x, respectively. We use $\lfloor x \rfloor_{2^p}$ for the largest integer less than or equal to x that is an integer power of 2. γ denotes the set of complex signal constellations of size M.

II. SPACE-TIME BLOCK CODED SPATIAL MODULATION (STBC-SM)

In the STBC-SM scheme, both STBC symbols and the indices of the transmit antennas from which these symbols are transmitted, carry information. We choose Alamouti's STBC, which transmits one symbol per channel use, as the core STBC due to its advantages in terms of spectral efficiency and simplified ML detection. In Alamouti's STBC, two complex information symbols (x_1 and x_2) drawn from an M-PSK or M-QAM constellation are transmitted by the codeword

$$\mathbf{X} = (\mathbf{x}_1 \quad \mathbf{x}_2) = \begin{pmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{pmatrix} \tag{1}$$

where columns and rows correspond to the transmit antennas and symbol intervals, respectively. For the STBC-SM scheme we extend the matrix in (1) to the antenna domain. Let us introduce the concept of STBC-SM by the following simple example. Consider a MIMO system with four transmit antennas which transmits the Alamouti's STBC using one of the following four codewords

$$\chi_1 = \{\mathbf{X}_{11}, \mathbf{X}_{12}\} = \left\{ \begin{pmatrix} x_1 & x_2 & 0 & 0 \\ -x_2^* & x_1^* & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & x_1 & x_2 \\ 0 & 0 & -x_2^* & x_1^* \end{pmatrix} \right\}$$

$$\chi_2 = \{\mathbf{X}_{21}, \mathbf{X}_{22}\} = \left\{ \begin{pmatrix} 0 & x_1 & x_2 & 0 \\ 0 & -x_2^* & x_1^* & 0 \end{pmatrix}, \begin{pmatrix} x_2 & 0 & 0 & x_1 \\ x_1^* & 0 & 0 & -x_2^* \end{pmatrix} \right\} e^{j\theta} \tag{2}$$

where $\chi_i, i = 1,2$ are the STBC-SM codebooks each containing two STBC-SM codewords $\mathbf{X}_{ij}, j = 1,2$ which do not interfere to each other. The resulting STBC-SM code is $\chi = \cup_{i=1}^{2} \chi_i$. A non-interfering codeword group having a elements is defined as a group of codewords satisfying $\mathbf{X}_{ij}\mathbf{X}_{ik}^H = \mathbf{0}_{2\times 2}, j,k = 1,2,\ldots,a, j \neq k$, that is they have no overlapping columns. In (2), θ is a rotation angle to be optimized to ensure maximum diversity and coding gain. Note that if θ is not considered, overlapping columns of codeword pairs from different codebooks would reduce the transmit diversity order to one. Assume now that we have four information bits (u_1, u_2, u_3, u_4) to be transmitted in two consecutive symbol intervals by the STBC-SM technique. The mapping rule for 2 bits/s/Hz transmission is given by Table 1 for the codebooks of (2) and binary phase-shift keying (BPSK) modulation, where a realization of any codeword is called as a transmission matrix. In Table 1, the first two information bits (u_1, u_2) are used to determine the antenna-pair position while the last two (u_3, u_4) determine the BPSK symbol pair.

A. STBC-SM System Design and Optimization

In this subsection, we generalize the STBC-SM scheme for MIMO systems with n_T transmit antennas by giving a general design algorithm. We first give the following definitions:

The minimum coding gain distance (CGD) [8] between two STBC-SM codewords $\mathbf{X}_{ij}$ and $\hat{\mathbf{X}}_{ij}$, where $\mathbf{X}_{ij}$ is transmitted and $\hat{\mathbf{X}}_{ij}$ is erroneously detected, is defined as

TABLE 1: STBC-SM MAPPING RULE FOR 2 BITS/S/HZ TRANSMISSION USING BPSK, FOUR TRANSMIT ANTENNAS AND ALAMOUTI'S STBC

Input Bits	Transmission Matrices	Input Bits	Transmission Matrices
0000	$\begin{pmatrix} 1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 \end{pmatrix}$	1000	$\begin{pmatrix} 0 & 1 & 1 & 0 \\ 0 & -1 & 1 & 0 \end{pmatrix} e^{j\theta}$
0001	$\begin{pmatrix} 1 & -1 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{pmatrix}$	1001	$\begin{pmatrix} 0 & 1 & -1 & 0 \\ 0 & 1 & 1 & 0 \end{pmatrix} e^{j\theta}$
0010	$\begin{pmatrix} -1 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \end{pmatrix}$	1010	$\begin{pmatrix} 0 & -1 & 1 & 0 \\ 0 & -1 & -1 & 0 \end{pmatrix} e^{j\theta}$
0011	$\begin{pmatrix} -1 & -1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix}$	1011	$\begin{pmatrix} 0 & -1 & -1 & 0 \\ 0 & 1 & -1 & 0 \end{pmatrix} e^{j\theta}$
0100	$\begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & -1 & 1 \end{pmatrix}$	1100	$\begin{pmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \end{pmatrix} e^{j\theta}$
0101	$\begin{pmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & 1 \end{pmatrix}$	1101	$\begin{pmatrix} -1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \end{pmatrix} e^{j\theta}$
0110	$\begin{pmatrix} 0 & 0 & -1 & 1 \\ 0 & 0 & -1 & -1 \end{pmatrix}$	1110	$\begin{pmatrix} 1 & 0 & 0 & -1 \\ -1 & 0 & 0 & -1 \end{pmatrix} e^{j\theta}$
0111	$\begin{pmatrix} 0 & 0 & -1 & -1 \\ 0 & 0 & 1 & -1 \end{pmatrix}$	1111	$\begin{pmatrix} -1 & 0 & 0 & -1 \\ -1 & 0 & 0 & 1 \end{pmatrix} e^{j\theta}$

$$\delta_{\min}(\mathbf{X}_{ij}, \hat{\mathbf{X}}_{ij}) = \min_{\mathbf{X}_{ij}, \hat{\mathbf{X}}_{ij}} \det(\mathbf{X}_{ij} - \hat{\mathbf{X}}_{ij})(\mathbf{X}_{ij} - \hat{\mathbf{X}}_{ij})^H. \tag{3}$$

The minimum CGD between two codebooks χ_i and χ_j is defined as

$$\delta_{\min}(\chi_i, \chi_j) = \min_{k,l} \delta_{\min}(\mathbf{X}_{ik}, \mathbf{X}_{jl}) \tag{4}$$

and the minimum CGD of STBC-SM code is defined by

$$\delta_{\min}(\chi) = \min_{i,j,i\neq j} \delta_{\min}(\chi_i, \chi_j). \tag{5}$$

Note that, $\delta_{\min}(\chi)$ corresponds to the determinant criterion given in [7] since the minimum CGD between non-interfering codewords of the same codebook is always greater than or equal to the right hand side of (5) and is also equal to that of Alamouti's STBC.

Unlike in the SM scheme, the number of transmit antennas in STBC-SM scheme need not to be an integer power of 2, since the pairwise combinations are chosen from n_T available transmit antennas for STBC transmission. This provides design flexibility. However, the total number of codeword combinations considered should be an integer power of 2. In the following, we give an algorithm to design the STBC-SM scheme:

1. Given the total number of transmit antennas n_T, calculate the number of possible antenna combinations for the transmission of Alamouti's STBC, i.e., the total number of STBC-SM codewords from $c = \lfloor \binom{n_T}{2} \rfloor_{2^p}$.
2. Calculate the number of codewords in each codebook $\chi_i, i = 1,2,\ldots,n-1$ from $a = \lfloor n_T/2 \rfloor$ and the total number of codebooks from $n = \lceil c/a \rceil$. Note that the last codebook χ_n does not need to have a codewords, i.e, its cardinality is $a' = c - a(n-1)$.
3. Start with the construction of χ_1 which contains a non-interfering codewords as

$$\chi_1 = \{(\mathbf{X} \quad \mathbf{0}_{2\times(n_T-2)}), \\ (\mathbf{0}_{2\times2} \quad \mathbf{X} \quad \mathbf{0}_{2\times(n_T-4)}), \\ (\mathbf{0}_{2\times4} \quad \mathbf{X} \quad \mathbf{0}_{2\times(n_T-6)}) \quad , \\ \vdots \\ (\mathbf{0}_{2\times2(a-1)} \quad \mathbf{X} \quad \mathbf{0}_{2\times(n_T-2a)})\} \tag{6}$$

where $\mathbf{X}$ is defined in (1).

4. With a similar approach, construct χ_i for $2 \le i \le n$ by considering the following two important facts:
   - Every codebook must contain non-interfering codewords chosen from pairwise combinations of n_T available transmit antennas.
   - Each codebook must be composed of codewords with antenna combinations that were never used in the construction of a previous codebook.
5. Determine the rotation angles θ_i for each χ_i, $2 \le i \le n$, that maximize $\delta_{min}(\chi)$ in (5) for a given signal constellation and antenna configuration, that is $\boldsymbol{\theta}_{opt} = \arg\max_{\boldsymbol{\theta}} \delta_{min}(\chi)$, where $\boldsymbol{\theta} = (\theta_2, \theta_3, \ldots, \theta_n)$.

As long as the STBC-SM codewords are generated by the algorithm described above, the choice of other antenna combinations is also possible but this would not improve the overall system performance. Since we have c antenna combinations, the resulting spectral efficiency of the STBC-SM scheme can be calculated as

$$m = \frac{1}{2}\log_2 cM^2 = \frac{1}{2}\log_2 c + \log_2 M \quad \text{[bits/s/Hz]} \tag{7}$$

where the factor $1/2$ normalizes for the two channel uses spanned by the STBC-SM codewords. The block diagram of the STBC-SM transmitter is shown in Fig. 1 in which $2m$ bits $u = (u_1, u_2, \ldots, u_{\log_2 c}, u_{\log_2 c+1}, \ldots, u_{\log_2 c+2\log_2 M})$ enter the STBC-SM transmitter during each two consecutive symbol intervals, where the first $\log_2 c$ bits determine the antenna-pair position $\ell = u_1 2^{\log_2 c-1} + u_2 2^{\log_2 c-2} + \cdots + u_{\log_2 c} 2^0$ which is associated with the corresponding antenna pair, while the last $2\log_2 M$ bits determine the symbol pair $(x_1, x_2) \in \gamma^2$. If we compare the spectral efficiency (7) of the STBC-SM scheme with that of Alamouti's scheme ($\log_2 M$ bits/s/Hz), we observe an increment of $0.5\log_2 c$ bits/s/Hz provided by the antenna modulation. We consider two different cases for the optimization of the STBC-SM scheme.

Case **1** - $n_T \le 4$: We have, in this case, two codebooks χ_1 and χ_2, and only one non-zero angle, say θ, to be optimized. It can be seen that $\delta_{\min}(\chi_1, \chi_2)$ is equal to the minimum CGD between any two interfering codewords. Assume that the interfering codewords are chosen as,

$$\mathbf{X}_{1k} = (\mathbf{x}_1 \quad \mathbf{x}_2 \quad \mathbf{0}_{2\times(n_T-2)}) \\ \mathbf{X}_{2l} = (\mathbf{0}_{2\times1} \quad \hat{\mathbf{x}}_1 \quad \hat{\mathbf{x}}_2 \quad \mathbf{0}_{2\times(n_T-3)})e^{j\theta} \tag{8}$$

where $\mathbf{X}_{1k} \in \chi_1$ is transmitted and $\hat{\mathbf{X}}_{1k} = \mathbf{X}_{2l} \in \chi_2$ is erroneously detected. We calculate the minimum CGD between $\mathbf{X}_{1k}$ and $\hat{\mathbf{X}}_{1k}$ from (3) as

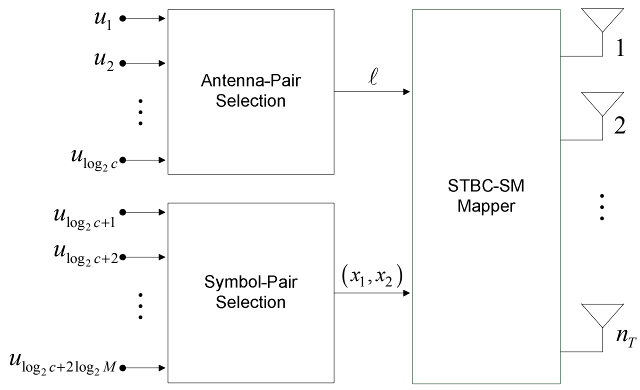

Fig. 1: Block diagram of the STBC-SM transmitter

$$\delta_{\min}(\mathbf{X}_{1k}, \hat{\mathbf{X}}_{1k}) \\ = \min_{\mathbf{X}_{1k}, \hat{\mathbf{X}}_{1k}} \det\begin{pmatrix} x_1 & x_2 - e^{j\theta}\hat{x}_1 & -e^{j\theta}\hat{x}_2 & \mathbf{0}_{1\times(n_T-3)} \\ -x_2^* & x_1^* + e^{j\theta}\hat{x}_2^* & -e^{j\theta}\hat{x}_1^* & \mathbf{0}_{1\times(n_T-3)} \end{pmatrix} \\ \times \begin{pmatrix} x_1^* & -x_2 \\ x_2^* - e^{-j\theta}\hat{x}_1^* & x_1 + e^{-j\theta}\hat{x}_2 \\ -e^{-j\theta}\hat{x}_2^* & -e^{-j\theta}\hat{x}_1 \\ \mathbf{0}_{(n_T-3)\times1} & \mathbf{0}_{(n_T-3)\times1} \end{pmatrix} \\ = \min_{\mathbf{X}_{1k}, \hat{\mathbf{X}}_{1k}} \Big\{ \big(\kappa - 2\mathrm{Re}\{\hat{x}_1^* x_2 e^{-j\theta}\}\big)\big(\kappa + 2\mathrm{Re}\{x_1 \hat{x}_2^* e^{j\theta}\}\big) - \\ |x_1|^2|\hat{x}_1|^2 - |x_2|^2|\hat{x}_2|^2 + 2\mathrm{Re}\{x_1\hat{x}_1 x_2^* \hat{x}_2^* e^{j2\theta}\} \Big\} \tag{9}$$

where $\kappa = \sum_{i=1}^{2}(|x_i|^2 + |\hat{x}_i|^2)$. Although maximization of $\delta_{\min}(\mathbf{X}_{1k}, \hat{\mathbf{X}}_{1k})$ with respect to θ is analytically possible for BPSK and quadrature phase-shift keying (QPSK) constellations, it becomes unmanageable for 16-QAM and 64-QAM. We compute $\delta_{\min}(\mathbf{X}_{1k}, \hat{\mathbf{X}}_{1k})$ as a function of $\theta \in [0, \pi/2]$ for BPSK, QPSK, 16-QAM and 64-QAM signal constellations by computer search and plot them in Fig. 2. These curves are denoted by $f_M(\theta)$ for $M = 2, 4, 16$ and 64, respectively. θ values maximizing these functions can be determined from Fig. 2 as follows:

$$\max_{\theta} \delta_{\min}(\chi) = \begin{cases} \max_{\theta} f_2(\theta) = 12, & \text{for} \quad \theta = 1.57 \text{ rad} \\ \max_{\theta} f_4(\theta) = 11.45, & \text{for} \quad \theta = 0.61 \text{ rad} \\ \max_{\theta} f_{16}(\theta) = 9.05, & \text{for} \quad \theta = 0.75 \text{ rad} \\ \max_{\theta} f_{64}(\theta) = 8.23, & \text{for} \quad \theta = 0.54 \text{ rad.} \end{cases}$$

Case **2** - $n_T > 4$: In this case, the number of codebooks, n, is greater than 2. Let the corresponding rotation angles to be optimized be denoted in ascending order by $\theta_1 = 0 < \theta_2 < \theta_3 < \cdots < \theta_n < p(\pi/2)$, where $p = 2$ for BPSK and $p = 1$ for QPSK. For BPSK and QPSK signaling, choosing

$$\theta_k = \begin{cases} (k-1)\pi/n & \text{for} \quad M = 2 \\ (k-1)\pi/2n & \text{for} \quad M = 4 \end{cases} \tag{10}$$

for $1 \le k \le n$ guarantees the maximization of the minimum CGD for the STBC-SM scheme. This could be explained as follows. For any n, we have to maximize $\delta_{\min}(\chi)$ as

$$\max \delta_{\min}(\chi) = \max \min_{i,j,i\ne j} \delta_{\min}(\chi_i, \chi_j) \\ = \max \min_{i,j,i\ne j} f_M(\theta_j - \theta_i) \tag{11}$$

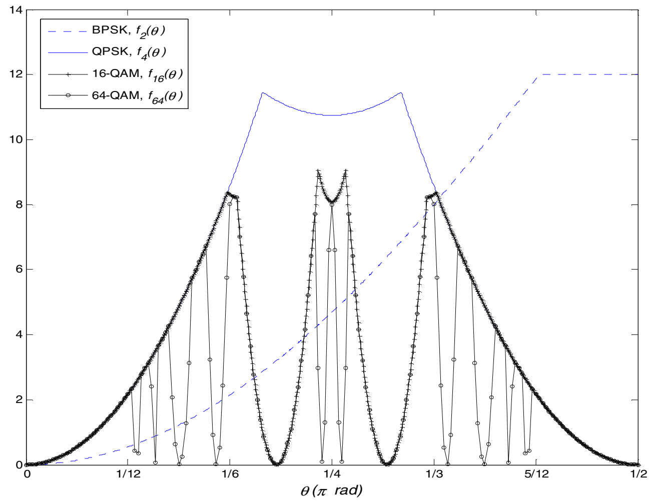

Fig.2 : Variation of $\delta_{\min}(\chi)$ given in (9) for BPSK, QPSK, 16-QAM and 64-QAM constellations

where $\theta_j > \theta_i$, for $j > i$ and the minimum CGD between codebooks χ_i and χ_j are directly determined by the differ-rence between their rotation angles. The proof of (11) is omitted here because of space limitations. Then, to maximize $\delta_{\min}(\chi)$, it is sufficient to maximize the minimum CGD between the consecutive codebooks χ_i and χ_{i+1}, $i = 1,2,\ldots,n-1$. For QPSK signaling, this is accomplished by dividing the interval $[0,\pi/2]$ into n equal sub-intervals and choosing $\theta_{i+1} - \theta_i = \pi/2n$ for $i = 1,2,\ldots,n-1$. The resulting maximum $\delta_{\min}(\chi)$ can be evaluated from (11) as

$$\begin{aligned}\max \delta_{\min}(\chi) &= \min\{f_4(\theta_2), f_4(\theta_3), \ldots, f_4(\theta_n)\} \\ &= f_4(\theta_2) = f_4(\pi/2n).\end{aligned} \quad (12)$$

Similar results are obtained for BPSK signaling except that $\pi/2n$ is replaced by π/n in (12). We obtain the corresponding maximum $\delta_{\min}(\chi)$ as $f_2(\theta_2) = f_2(\pi/n)$. On the other hand, for 16-QAM and 64-QAM signaling, the selection of $\{\theta_k\}$'s in integer multiples of $\pi/2n$ would not guarantee to maximize $\delta_{\min}(\chi)$ since the behavior of the functions $f_{16}(\theta)$ and $f_{64}(\theta)$ is very non-linear, having several zeros in $[0,\pi/2]$. However, our extensive computer search has indicated that for 16-QAM with $n \le 6$, the rotation angles chosen as $\theta_k = (k-1)\pi/2n$ for $1 \le k \le n$ are still optimum. But for 16-QAM signaling with $n > 6$ as well as for 64-QAM signaling with $n > 2$, the optimal $\{\theta_k\}$'s should be determined by an exhaustive computer search.

In Table 2, we summarize the basic parameters of the STBC-SM system for $3 \le n_T \le 8$. We observe that increasing the number of transmit antennas results in increasing spectral efficiency achieved by the STBC-SM scheme. However, this requires a larger number of angles to be optimized and causes some reduction in the minimum CGD.

We now give an example for the codebook generation process by the STBC-SM design algorithm, presented above.

TABLE 2: BASIC PARAMETERS OF THE STBC-SM SYSTEM FOR DIFFERENT NUMBER OF TRANSMIT ANTENNAS

n_T	c	a	n	$\delta_{\min}(\chi)$			m [bits/s/Hz]
				$M=2$	$M=4$	$M=16$	
3	2	1	2	12	11.45	9.05	$0.5+\log_2 M$
4	4	2	2	12	11.45	9.05	$1+\log_2 M$
5	8	2	4	4.69	4.87	4.87	$1.5+\log_2 M$
6	8	3	3	8.00	8.57	8.31	$1.5+\log_2 M$
7	16	3	6	2.14	2.18	2.18	$2+\log_2 M$
8	16	4	4	4.69	4.87	4.87	$2+\log_2 M$

Design Example: From Table 2, for $n_T = 6$, we have $c = 8$, $a = n = 3$ and optimized angles are $\theta_2 = \pi/3$, $\theta_3 = 2\pi/3$ for BPSK and $\theta_2 = \pi/6$, $\theta_3 = \pi/3$ for QPSK and 16-QAM. The maximum of $\delta_{\min}(\chi)$ is calculated for BPSK, QPSK and 16-QAM constellations as

$$\max \delta_{\min}(\chi) = \begin{cases} f_2(\pi/3) = 8.00 & \text{for } M = 2 \\ f_4(\pi/6) = 8.57 & \text{for } M = 4 \\ f_{16}(\pi/6) = 8.31 & \text{for } M = 16. \end{cases}$$

According to the design algorithm, the codebooks can be constructed as below,

$$\chi_1 = \{(\mathbf{x}_1 \;\; \mathbf{x}_2 \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0}), (\mathbf{0} \;\; \mathbf{0} \;\; \mathbf{x}_1 \;\; \mathbf{x}_2 \;\; \mathbf{0} \;\; \mathbf{0}), (\mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{x}_1 \;\; \mathbf{x}_2)\}$$

$$\chi_2 = \{(\mathbf{0} \;\; \mathbf{x}_1 \;\; \mathbf{x}_2 \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0})e^{j\theta_2}, (\mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{x}_1 \;\; \mathbf{x}_2 \;\; \mathbf{0})e^{j\theta_2}, (\mathbf{x}_2 \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{x}_1)e^{j\theta_2}\}$$

$$\chi_3 = \{(\mathbf{x}_1 \;\; \mathbf{0} \;\; \mathbf{x}_2 \;\; \mathbf{0} \;\; \mathbf{0} \;\; \mathbf{0})e^{j\theta_3}, (\mathbf{0} \;\; \mathbf{x}_1 \;\; \mathbf{0} \;\; \mathbf{x}_2 \;\; \mathbf{0} \;\; \mathbf{0})e^{j\theta_3}\}$$

where $\mathbf{0}$ denotes the 2×1 all-zero vector. Since there are $\binom{6}{2} = 15$ possible antenna combinations, 7 of them are discarded to obtain 8 codewords. Note that, the choice of other combinations does not affect $\delta_{\min}(\chi)$. In other words, the codebooks given above represent only one of the possible realizations of the STBC-SM scheme for six transmit antennas.

B. Optimal ML Decoder for the STBC-SM Scheme

In this subsection, we formulate the ML decoder for the STBC-SM scheme. The system with n_T transmit and n_R receive antennas is considered in the presence of a quasi-static Rayleigh fading MIMO channel. The received $2 \times n_R$ signal matrix $\mathbf{Y}$ can be expressed as

$$\mathbf{Y} = \sqrt{\rho/\mu}\,\mathbf{X}_\chi \mathbf{H} + \mathbf{N} \quad (13)$$

where $\mathbf{X}_\chi \in \chi$ is the $2 \times n_T$ STBC-SM transmission matrix, transmitted over two channel uses and μ is the normalization factor to ensure that ρ is the average signal-to-noise ratio (SNR) at each receive antenna. $\mathbf{H}$ and $\mathbf{N}$ denote the $n_T \times n_R$ channel matrix and $2 \times n_R$ noise matrix, respectively. 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 means and unit variances. We assume that $\mathbf{H}$ remains constant during the transmission of a codeword and takes independent values from one codeword to another as well as being known at the receiver, but not at the transmitter.

Assuming n_T transmit antennas are employed, the STBC-SM code has c codewords from which cM^2 different transmission matrices can be constructed. An ML decoder must make an exhaustive search over all possible cM^2 transmission matrices, and decides in favor of the matrix which minimizes the following metric:

$$\hat{\mathbf{X}}_\chi = \arg\min_{\mathbf{X}_\chi \in \chi} \left\| \mathbf{Y} - \sqrt{\rho/\mu}\, \mathbf{X}_\chi \mathbf{H} \right\|^2. \quad (14)$$

The minimization in (14) can be simplified due to the orthogonality of Alamouti's STBC as follows. The decoder can extract the embedded information symbol vector from (13), and obtain the following equivalent channel model:

$$\mathbf{y} = \sqrt{\rho/\mu}\, \boldsymbol{\mathcal{H}}_\chi \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \mathbf{n} \quad (15)$$

where $\boldsymbol{\mathcal{H}}_\chi$ is the $2n_R \times 2$ equivalent channel matrix [9] of the Alamouti coded SM scheme which has c different realizations denoted as $\boldsymbol{\mathcal{H}}_\ell$, $0 \le \ell \le c-1$ according to the STBC-SM codewords; $\mathbf{y}$ and $\mathbf{n}$ represent the $2n_R \times 1$ equivalent received signal and noise vectors, respectively. Due to the orthogonality of Alamouti's STBC, the columns of $\boldsymbol{\mathcal{H}}_\chi$ are orthogonal to each other for all cases, and, consequently no ICI occurs in our scheme as in SM. For the ℓth combination, the receiver determines the ML estimates of x_1 and x_2 using the decomposition as follows [10], resulting from the orthogonality of $\mathbf{h}_{\ell,1}$ and $\mathbf{h}_{\ell,2}$:

$$\begin{aligned} \hat{x}_{1,\ell} &= \arg\min_{x_1 \in \gamma} \left\| \mathbf{y} - \sqrt{\rho/\mu}\, \mathbf{h}_{\ell,1} x_1 \right\|^2 \\ \hat{x}_{2,\ell} &= \arg\min_{x_2 \in \gamma} \left\| \mathbf{y} - \sqrt{\rho/\mu}\, \mathbf{h}_{\ell,2} x_2 \right\|^2 \end{aligned} \quad (16)$$

where $\boldsymbol{\mathcal{H}}_\ell = [\mathbf{h}_{\ell,1} \quad \mathbf{h}_{\ell,2}]$, $0 \le \ell \le c-1$, and $\mathbf{h}_{\ell,j}, j = 1,2$, is a $2n_R \times 1$ column vector. The associated minimum ML metrics $m_{1,\ell}$ and $m_{2,\ell}$ for x_1 and x_2 are

$$\begin{aligned} m_{1,\ell} &= \min_{x_1 \in \gamma} \left\| \mathbf{y} - \sqrt{\rho/\mu}\, \mathbf{h}_{\ell,1} x_1 \right\|^2 \\ m_{2,\ell} &= \min_{x_2 \in \gamma} \left\| \mathbf{y} - \sqrt{\rho/\mu}\, \mathbf{h}_{\ell,2} x_2 \right\|^2 \end{aligned} \quad (17)$$

respectively. Since $m_{1,\ell}$ and $m_{2,\ell}$ are calculated by the ML decoder for the ℓth combination, their summation $m_\ell = m_{1,\ell} + m_{2,\ell}$, $0 \le \ell \le c-1$ gives the total ML metric for the ℓth combination. Finally, the receiver makes a decision by choosing the minimum antenna combination metric as $\hat{\ell} = \arg\min_\ell m_\ell$ for which $(\hat{x}_1, \hat{x}_2) = (\hat{x}_{1,\hat{\ell}}, \hat{x}_{2,\hat{\ell}})$. As a result, the total number of ML metric calculations in (14) is reduced from cM^2 to $2cM$, yielding a linear decoding complexity as for the SM scheme with optimal decoding which requires Mn_T metric calculations. Obviously, since $c \ge n_T$ for $n_T \ge 4$, there will be a linear increase in ML decoding complexity with STBC-SM as compared to the SM scheme. However, as we will show in the next section, this insignificant increase in decoding complexity is compensated by significant performance improvement provided by the STBC-SM over SM.

The last step of the decoding process is the demapping operation based on the look-up table used at the transmitter, to recover the input bits from $\hat{\ell}$ and the information symbols $\hat{x}_1$ and $\hat{x}_2$. The block diagram of the ML decoder described above is given in Fig. 3.

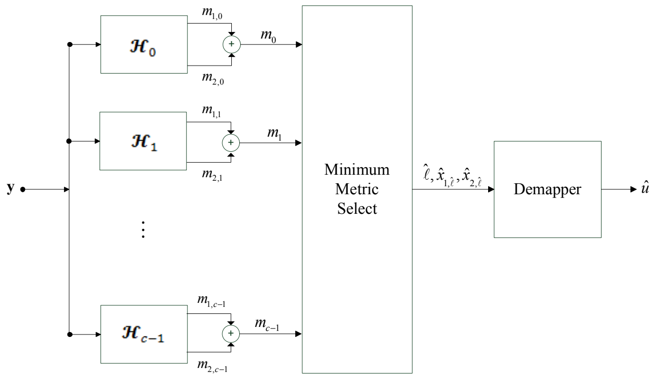

Fig. 3: Block diagram of the STBC-SM ML receiver

III. SIMULATION RESULTS AND COMPARISONS

In this section, we present simulation results for the STBC-SM system with different numbers of transmit antennas and make comparisons with the SM, V-BLAST, rate-3/4 orthogonal STBC (OSTBC) for four transmit antennas [8] and Alamouti's STBC. The bit error rate (BER) performance of these systems was evaluated by Monte Carlo simulations for various spectral efficiencies as a function of the average SNR per receive antenna (ρ) and in all cases we assumed four receive antennas. All performance comparisons are made for a BER value of 10^{-5}. The SM system uses the optimal decoder derived in [4]. The V-BLAST system uses minimum mean square error (MMSE) detection with ordered successive interference cancellation (SIC) decoding [11].

In Fig. 4, the BER curves of STBC-SM with $n_T = 4$ and QPSK, SM with $n_T = 4$ and BPSK, V-BLAST with $n_T = 3$ and BPSK, OSTBC with 16-QAM, and Alamouti's STBC with 8-QAM are evaluated for 3 bits/s/Hz transmission. We observe that STBC-SM provides SNR gains of 3.8 dB, 5.1 dB, 2.8 dB and 3.4 dB over SM, V-BLAST, OSTBC and Alamouti's STBC, respectively.

In Fig. 5, the BER curves of STBC-SM with $n_T = 8$ and QPSK, SM with $n_T = 8$ and BPSK, V-BLAST with $n_T = 2$ and QPSK, OSTBC with 32-QAM, and Alamouti's STBC with 16-QAM are compared for 4 bits/s/Hz. It is seen that STBC-SM provides SNR gains of 3.5 dB, 5 dB, 4.7 dB and 4.4 dB over, SM, V-BLAST, OSTBC and Alamouti's STBC, respectively.

In Fig. 6 we extend our simulation studies to 6 bits/s/Hz transmission. As seen from Fig. 6, STBC-SM with $n_T = 8$ and 16-QAM provides SNR gains of 3.4 dB, 3.7 dB, 8.6 dB and 5.4 dB over SM with $n_T = 8$ and 8-QAM, V-BLAST with $n_T = 3$ and QPSK, OSTBC with 256-QAM and Alamouti's STBC with 64-QAM, respectively.

By considering the BER curves in Figs. 4-6, we conclude that the BER performance gap between the STBC-SM and SM or V-BLAST systems increases for high SNR values due to the second order transmit diversity advantage of the STBC-SM scheme. We also observe that although having a less diversity order, STBC-SM outperforms rate-3/4 OSTBC due to its higher transmission rate.

IV. CONCLUSIONS

In this paper, we have introduced a novel high-rate, low complexity MIMO transmission scheme, called STBC-SM, as an alternative to existing techniques such as SM and V-BLAST. The proposed new transmission scheme employs both APM techniques and antenna indices to convey information and exploits the transmit diversity potential of MIMO channels. A general algorithm has been presented for the construction of the STBC-SM scheme for any number of transmit antennas in which the STBC-SM scheme was optimized by deriving its diversity and coding gains to reach optimal performance. It was shown by computer simulations that the STBC-SM offers significant improvements in BER performance compared to SM and V-BLAST systems (approximately 3-5 dB depending on the spectral efficiency) with an acceptable linear increase in decoding complexity. We conclude that the STBC-SM scheme can be useful for high-rate, low complexity, future wireless communication systems like LTE and WiMAX.

V. REFERENCES

[1] R. Mesleh, H. Haas, C. W. Ahn, and S. Yun, "Spatial modulation–A new low complexity spectral efficiency enhancing technique," in *Proc. Conf. Commun. and Networking in China*, Beijing, China, pp. 1-5, Oct. 2006.

[2] R. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2228–2241, July 2008.

[3] P. Wolniansky, G. Foschini, G. Golden, and R. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," in *Proc. International Symp. Signals, Systems, Electronics (ISSSE'98)*, Pisa, Italy, pp. 295-300, Sept. 1998.

[4] J. Jeganathan, A. Ghrayeb, and L. Szczecinski, "Spatial modulation: optimal detection and performance analysis," *IEEE Commun. Lett.*, vol. 12, no. 8, pp. 545-547, Aug. 2008.

[5] J. Jeganathan, A. Ghrayeb, L. Szczecinski, and A. Ceron, "Space-shift keying modulation for MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3692-3703, July 2009.

[6] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451-1458, Oct. 1998.

[7] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communications: performance criterion and code construction," *IEEE Trans. Inf. Theory*, 1998, vol. 44, no. 2, pp. 744-765, Mar. 1998.

[8] H. Jafarkhani, *Space-Time Coding, Theory and Practice*, Cambridge University Press, Cambridge, UK, 2005.

[9] B. Hassibi and B. M. Hochwald, "High-rate codes that are linear in space and time," *IEEE Trans. Inf. Theory*, vol. 48, no. 7, pp. 1804-1824, July 2002.

[10] X. Guo and X.-G. Xia, "On full diversity space-time block codes with partial interference cancellation group decoding," *IEEE Trans. Inf. Theory*, vol. 55, no. 10, pp. 4366-4385, Oct. 2009.

[11] R. Böhnke, D. Wübben, V. Kühn, and K. D. Kammeyer, "Reduced complexity MMSE detection for BLAST architectures," in *Proc. IEEE Global Commun. Conf.*, San Francisco, CA, USA, pp. 2258-2262, Dec. 2003.

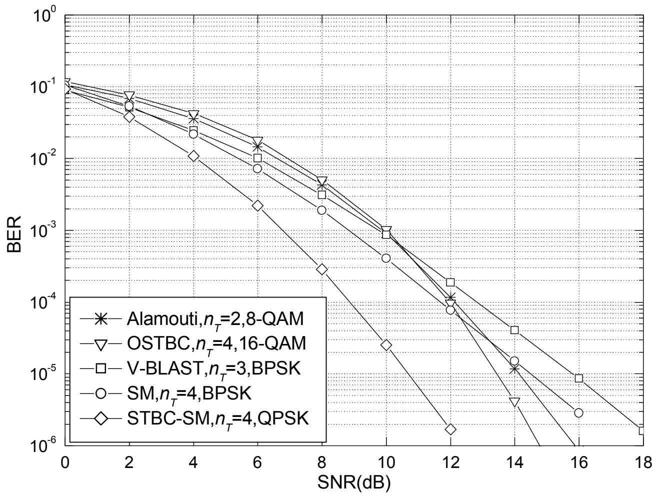

Fig 4: BER performance at 3 bits/s/Hz for STBC-SM, SM, V-BLAST, OSTBC and Alamouti's STBC schemes

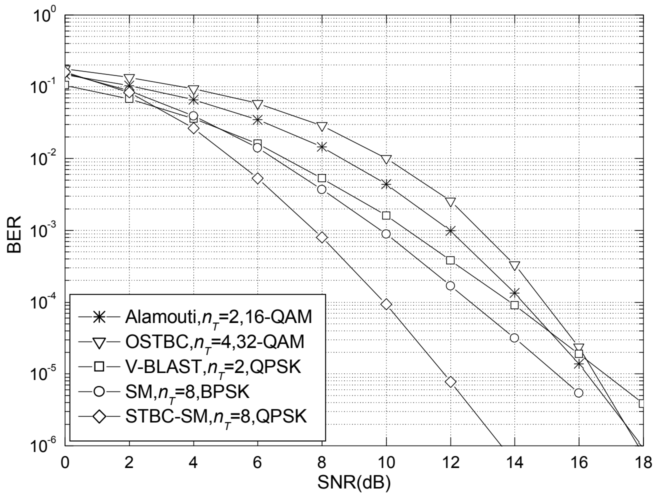

Fig 5: BER performance at 4 bits/s/Hz for STBC-SM, SM, V-BLAST, OSTBC and Alamouti's STBC schemes

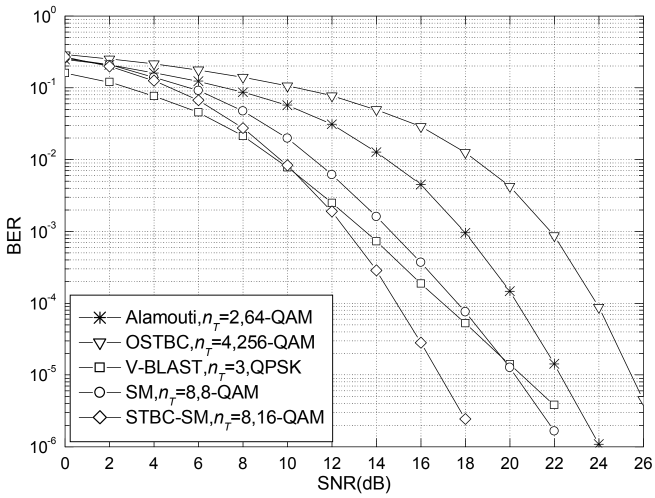

Fig 6: BER performance at 6 bits/s/Hz for STBC-SM, SM, V-BLAST, OSTBC and Alamouti's STBC schemes