Space-Time Quadrature Spatial Modulation

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***Abstract*—In this paper, a new multiple-input multiple-output (MIMO) transmission technique, which is called space-time quadrature spatial modulation (ST-QSM), is proposed. The ST-QSM scheme aims to provide a diversity gain for quadrature spatial modulation (QSM) by combining it with the Alamouti or ABBA space-time block codes (STBCs). In the ST-QSM scheme, the transmit antennas are subdivided into two groups and the information is conveyed with the indices of the antennas in these groups, in addition to the two complex modulated symbols. These two complex symbols are decomposed into their in-phase and quadrature components and independently transmitted through their corresponding active transmit antennas, whose indices are determined from the first and the second groups. Then, the Alamouti's STBC or ABBA STBC principle is applied to each group depending on the number of antennas in them. The superior error performance of the proposed ST-QSM scheme is shown by computer simulations compared to QSM, Alamouti's STBC and space-time block coded spatial modulation (STBC-SM) schemes. In addition, the pairwise error probability (PEP) of ST-QSM is derived and the average bit error probability (ABEP) over uncorrelated Rayleigh fading channels is obtained for different MIMO configurations.**

***Index Terms*—MIMO systems, spatial modulation (SM), quadrature SM (QSM), space-time block codes (STBC).**

I. Introduction

Multiple-input multiple-output (MIMO) transmission has been a breakthrough technology to increase the link reliability and capacity of the wireless communications systems compared to single-input single-output (SISO) systems. The increasing demand for high data rates and the scarcity of the wireless spectrum has led researchers to develop highly efficient MIMO transmission technologies such as spatial multiplexing and space time block codes (STBCs) in order to achieve multiplexing and diversity gain, respectively.

Spatial modulation (SM) [1] is one of the promising MIMO transmission techniques, which has become increasingly popular in the past few years. SM scheme uses an innovative way for transmitting information, that is, it carries information by transmit antenna indices in addition to M-ary signal constellations (such as M-ary quadrature amplitude modulation or phase shift keying (M-QAM/PSK). Unlike traditional spatial multiplexing techniques [2], in the SM scheme only one of the available transmit antennas is activated and the information is transmitted through this activated antenna. Therefore, the SM scheme achieves a substantial increase in spectral efficiency compared to single-input single-output (SISO) systems by using only one radio frequency (RF) chain at the transmitter. Since the SM scheme improves the spectral efficiency in a more energy efficient way than the traditional spatial multiplexing systems, it has become an alternative MIMO transmission technique in recent years [3]. Therefore, various SM schemes are designed in order to achieve higher multiplexing and/or diversity gain.

Space-time block coded spatial modulation (STBC-SM) [4] is a novel transmission method, which combines the traditional SM scheme with STBC in order to simultaneously achieve multiplexing and diversity gain for any number of transmit antennas. In STBC-SM, information bits determine one of the combinations of the active antenna pairs and the corresponding two M-ary modulated symbols. These two symbols are transmitted over their corresponding active antennas using Alamouti's STBC [5] due to its detection simplicity. The data rate achieved by STBC-SM is $m = \frac{1}{2}\log_2(c) + \log_2(M)$ bits per channel use (bpcu), where $c = 2^{\lfloor \log_2 \binom{N_t}{2} \rfloor}$ is the total number of different active antenna pairs, N_t is the number of transmit antennas and $\lfloor \cdot \rfloor$ is the floor function.

Generalized spatial modulation (GSM) schemes [6], [7] are proposed to boost the spectral efficiency of the traditional SM by increasing the number of active transmit antennas. In GSM schemes, the incoming information bits determine one of the combinations of the transmit antennas and their corresponding M-ary constellation symbols. The idea of increasing the number of active transmit antennas in order to improve the spectral efficiency appears in different MIMO scheme such as the recently introduced scheme of quadrature spatial modulation (QSM) [8]. In the QSM scheme, the incoming information bits determine a complex M-QAM symbol and two independent transmit antennas. This complex symbol is decomposed into its in-phase and quadrature components which are independently transmitted through their corresponding active transmit antennas. Since the transmitted components are orthogonal to each other, the inter-channel interference (ICI) is avoided at the receiver. The QSM technique has attracted significant attention in recent times. In [9], a near-optimal detector for the QSM scheme is reported and in [10], the performance of QSM is improved via cooperative relaying systems.

This paper introduces a new MIMO transmission method, called *space-time quadrature spatial modulation* (ST-QSM), which achieves a second order diversity gain for the QSM scheme. The overall transmission matrix of the ST-QSM scheme is obtained by the application of the ABBA or Alamouti's STBC principle to two independent QSM transmission vectors. In the ST-QSM scheme, the QSM technique is applied

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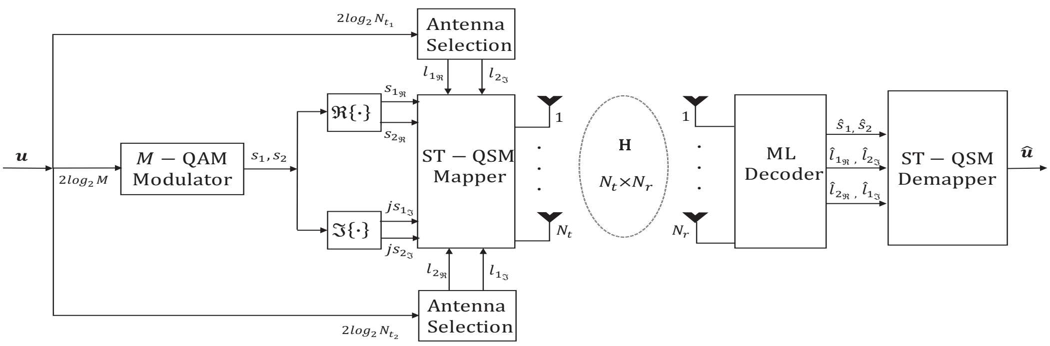

Fig. 1. System model of ST-QSM scheme

to two complex M-QAM symbols, that is, the symbols are decomposed into their in-phase and quadrature components, which are independently transmitted through their corresponding active antennas. The proposed ST-QSM scheme is designed for 4, 6 and 8 transmit antennas. The available transmit antennas are divided into two groups, each consists of two or four transmit antennas. The real component of the first symbol and imaginary component of the second symbol are independently transmitted through one of the transmit antennas of the first group, while the real component of the second symbol and imaginary component of the first symbol are independently transmitted through one of the transmit antennas of the second group. Then, in the second time slot, to achieve a diversity gain, either Alamouti's STBC [5] or ABBA STBC [11] transmission principle is applied to the signal vectors of both groups depending on the number of antennas in each of them. The bit error rate (BER) performance of the ST-QSM scheme is compared with the QSM scheme and the existing schemes in the literature such as STBC-SM and Alamouti's STBC. It is clearly shown by computer simulations that ST-QSM exhibits a better BER performance than the QSM, STBC-SM and Alamouti's STBC schemes. Moreover, in order to support our results, the analytical bit error performance (ABEP) of the proposed system is obtained for uncorrelated Rayleigh fading channels.

The rest of the paper is organized as follows. In Section II, the system model of the proposed ST-QSM scheme is given. In Section III, the analysis of ABEP of the system is performed. The computer simulation results are discussed in Section IV and the paper is concluded in Section V.

II. Space-Time Quadrature Spatial Modulation System Model

In the ST-QSM scheme, instead of considering all transmit antenna indices as a whole unlike SM and QSM schemes, the total transmit antennas are split into two groups and the information is independently conveyed by the indices of the antennas in each group in addition to two M-QAM constellation symbols. In order to achieve diversity gain, Alamouti or ABBA STBC, is applied to the transmission vectors of both groups depending on the number of transmit antennas in each group. We use the Alamouti's STBC and ABBA STBC for the group(s) with two or four transmit antennas, respectively. The general transmission matrix of Alamouti's STBC is given as

$$\mathbf{C}_2 = \begin{pmatrix} x_{11} & x_{12} \\ -x_{12}^* & x_{11}^* \end{pmatrix} \tag{1}$$

where x_{11} and x_{12} are M-ary symbols and $(\cdot)^*$ denotes the complex conjugate. The ABBA STBC consists of two successive Alamouti codes with the following general transmission matrix:

$$\mathbf{C}_4 = \begin{pmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ -x_{12}^* & x_{11}^* & -x_{14}^* & x_{13}^* \end{pmatrix} \tag{2}$$

where x_{13} and x_{14} are two additional M-ary symbols.

Let us consider an $N_t \times N_r$ MIMO configuration, where N_t and N_r denote the number of transmit and receive antennas, respectively. The available N_t transmit antennas are subdivided into two groups, where N_{t_1} and N_{t_2} stand for the number of transmit antennas in the first and the second group, respectively and $N_t = N_{t_1} + N_{t_2}$. Two M-QAM modulated symbols s_1 and s_2 are decomposed into their real and imaginary parts, where $s_i = s_{i_\Re} + js_{i_\Im}$ for $i \in \{1, 2\}$. The real component of the first symbol $s_{1_\Re}$ and the imaginary component of the second symbol $js_{2_\Im}$ are independently transmitted over $l_{1_\Re}$th and $l_{2_\Im}$th transmit antennas of the first group with N_{t_1} transmit antennas, where $l_{1_\Re}, l_{2_\Im} \in \{1, 2, \ldots, N_{t_1}\}$ are the indices of the active transmit antennas in the first group, and result in a transmission vector of $\mathbf{a}^1 \in \mathbb{C}^{1\times N_{t_1}}$. Similarly, the real component of the second symbol $s_{2_\Re}$ and the imaginary component of the first symbol $js_{1_\Im}$ are independently transmitted over $l_{2_\Re}$th and $l_{1_\Im}$th transmit antennas of the second group with N_{t_2} transmit antennas, where $l_{2_\Re}, l_{1_\Im} \in \{1, 2, \ldots, N_{t_2}\}$ are the indices of the active transmit antennas in the second group, and result in a transmission vector of $\mathbf{b}^1 \in \mathbb{C}^{1\times N_{t_2}}$. As a result, we obtain

$$\mathbf{C}_{N_{t_1}} = \begin{pmatrix} \mathbf{a}^1 \\ \mathbf{a}^2 \end{pmatrix} \qquad \mathbf{C}_{N_{t_2}} = \begin{pmatrix} \mathbf{b}^1 \\ \mathbf{b}^2 \end{pmatrix}. \tag{3}$$

In (3), $\mathbf{C}_{N_{t_1}} \in \mathbb{C}^{2\times N_{t_1}}$ and $\mathbf{C}_{N_{t_2}} \in \mathbb{C}^{2\times N_{t_2}}$ are the matrices that collect the transmitted signals of the first and second groups, respectively, which have the structures of Alamouti (1) or ABBA STBC (2) depending on the number of antennas in each group, where $\mathbf{a}^2 \in \mathbb{C}^{1\times N_{t_1}}$ and $\mathbf{b}^2 \in \mathbb{C}^{1\times N_{t_2}}$ are the transmission vectors of the first and second groups, which are transmitted in the second time slot. The overall transmission matrix $\mathbf{X} \in \mathbb{C}^{2\times N_t}$ of the ST-QSM scheme is constructed from $\mathbf{C}_{N_{t_1}}$ and $\mathbf{C}_{N_{t_2}}$ as

$$\mathbf{X} = \begin{bmatrix} \mathbf{a}^1 & \mathbf{b}^1 \\ \mathbf{b}^2 & \mathbf{a}^2 \end{bmatrix}. \tag{4}$$

The data rate achieved by the ST-QSM scheme is $m = \log_2 M + \log_2 N_{t_1} + \log_2 N_{t_2}$ bpcu. Design examples of ST-QSM system are given in the following subsections for 4, 6 and 8 transmit antennas.

A. ST-QSM scheme for $N_t = 4$

The ST-QSM scheme for $N_t = 4$ is explained with the following example. For this case, $\mathbf{X}$ of (4) has the following generic structure:

$$\mathbf{X} = \left[\begin{array}{cc|cc} x_{11} & x_{12} & x_{13} & x_{14} \\ -x_{14}^* & x_{13}^* & -x_{12}^* & x_{11}^* \end{array}\right] \tag{5}$$

where $x_{11}, x_{12} \in \{s_{1_\Re}, js_{2_\Im}, s_{1_\Re} + js_{2_\Im}, 0\}$ and $x_{13}, x_{14} \in \{s_{2_\Re}, js_{1_\Im}, s_{2_\Re} + js_{1_\Im}, 0\}$.

The block diagram of the ST-QSM scheme is given in Fig. 1. Assume that $2m$-length information bit sequence given as $\{0\,1\,1\,1\,0\,0\,1\,0\}$, is transmitted over a MIMO system using $N_t = 4$ transmit antennas and 4-QAM. These N_t transmit antennas are divided into two groups, where the number of antennas in each group becomes $N_{t_1} = N_{t_2} = 2$. The first $\log_2 M$ bits $\{0\,1\}$ determine the first 4-QAM symbol $(s_1 = -1 - j)$ and the following $\log_2(N_{t_1}N_{t_2})$ bits $\{1\,1\}$ independently activate one of the antennas in each group as $l_{1_\Re} = 1$ and $l_{1_\Im} = 1$ in order to transmit $s_{1_\Re} = -1$ and $js_{1_\Im} = -j$, respectively. Therefore, transmission of the symbol s_1 results in a transmission vector of $\mathbf{x}_1 = [\underbrace{-1\ 0}_{N_{t_1}=2} \,|\, \underbrace{-j\ 0}_{N_{t_2}=2}]$. Similarly, the remaining $\log_2 M$ bits $\{0\,0\}$ determine a second 4-QAM symbol $(s_2 = -1 + j)$ and the last $\log_2(N_{t_1}N_{t_2})$ bits $\{1\,0\}$ independently activate one of the antennas in each group as $l_{2_\Re} = 1$ and $l_{2_\Im} = 2$ in order to transmit $s_{2_\Re} = -1$ and $js_{2_\Im} = j$, respectively. The transmission of the symbol s_2 results in a transmission vector of $\mathbf{x}_2 = [\underbrace{\ 0\ j\ }_{N_{t_1}=2} \,|\, \underbrace{-1\ 0}_{N_{t_2}=2}]$. Therefore, the superimposition of $\mathbf{x}_1$ and $\mathbf{x}_2$ becomes $\left[\mathbf{x}_1 + \mathbf{x}_2\right] = [\underbrace{-1\ j}_{N_{t_1}=2} \,|\, \underbrace{-1-j\ 0}_{N_{t_2}=2}]$, where the first part with $N_{t_1} = 2$ antennas corresponds to the vector of $\mathbf{a}^1 = [-1\ \ j]$, while the second part with $N_{t_2} = 2$ antennas corresponds to the vector of $\mathbf{b}^1 = [-1-j\ 0]$. Since $N_{t_1} = N_{t_2} = 2$, both $\mathbf{C}_{N_{t_1}}$ and $\mathbf{C}_{N_{t_2}}$ matrices follow the structure of Alamouti's STBC (1) matrix as follows: $\mathbf{C}_{N_{t_1}} = \begin{bmatrix} -1 & j \\ j & -1 \end{bmatrix}$, $\mathbf{C}_{N_{t_2}} = \begin{bmatrix} -1-j & 0 \\ 0 & -1+j \end{bmatrix}$. Therefore, the overall transmission matrix $\mathbf{X}$ given in (4) is constructed as $\mathbf{X} = \left[\begin{array}{cc|cc} -1 & j & -1-j & 0 \\ 0 & -1+j & j & -1 \end{array}\right]$.

B. ST-QSM schemes for $N_t = 8$ and $N_t = 6$

In this subsection, design examples of the ST-QSM scheme for $N_t = 8$ and $N_t = 6$ are given. The general transmission matrix of the ST-QSM scheme for $N_t = 8$ is given as

$$\mathbf{X} = \left[\begin{array}{cccc|cccc} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} & x_{16} & x_{17} & x_{18} \\ -x_{16}^* & x_{15}^* & -x_{18}^* & x_{17}^* & -x_{12}^* & x_{11}^* & -x_{14}^* & x_{13}^* \end{array}\right] \tag{6}$$

where $x_{11}, x_{12}, x_{13}, x_{14} \in \{s_{1_\Re}, js_{2_\Im}, s_{1_\Re} + js_{2_\Im}, 0\}$ and $x_{15}, x_{16}, x_{17}, x_{18} \in \{s_{2_\Re}, js_{1_\Im}, s_{2_\Re} + js_{1_\Im}, 0\}$.

In the ST-QSM scheme for $N_t = 8$, the number of antennas in each group is $N_{t_1} = N_{t_2} = 4$. Assume that the incoming data bits determine $s_1 = 5 + 3j$ and $s_2 = -7 - j$ complex data symbols and the active antenna indices of $l_{1_\Re} = 1$, $l_{1_\Im} = 3$, $l_{2_\Re} = 2$ and $l_{2_\Im} = 3$. The components of $s_{1_\Re}$, $js_{1_\Im}$, $s_{2_\Re}$ and $js_{2_\Im}$ are independently transmitted through the active antenna indices of $l_{1_\Re}$, $l_{1_\Im}$, $l_{2_\Re}$ and $l_{2_\Im}$, which results in the transmission vectors of $\mathbf{x}_1 = [\underbrace{5\,0\,0\,0}_{N_{t_1}=4} \,|\, \underbrace{0\,0\,3j\,0}_{N_{t_2}=4}]$ and $\mathbf{x}_2 = [\underbrace{0\,0\,-j\,0}_{N_{t_1}=4} \,|\, \underbrace{0\,-7\,0\,0}_{N_{t_2}=4}]$: therefore, the superimposition of $\mathbf{x}_1$ and $\mathbf{x}_2$ becomes $\left[\mathbf{x}_1 + \mathbf{x}_2\right] = [\underbrace{5\ 0\ -j\ 0}_{N_{t_1}=4} | \underbrace{0\ -7\ 3j\ 0}_{N_{t_2}=4}]$, where the first part with $N_{t_1} = 4$ antennas corresponds to the vector of $\mathbf{a}^1 = [5\,0 - j\,0]$, while the second part with $N_{t_2} = 4$ antennas corresponds to the vector of $\mathbf{b}^1 = [0\ -7\ 3j\ 0]$.

Since the number of antennas in each group is four ($N_{t_1} = N_{t_2} = 4$), both of $\mathbf{C}_{N_{t_1}}$ and $\mathbf{C}_{N_{t_2}}$ matrices follows the structure of ABBA STBC (2) matrix. Therefore, $\mathbf{C}_{N_{t_1}}$ and $\mathbf{C}_{N_{t_2}}$ become $\mathbf{C}_{N_{t_1}} = \begin{bmatrix} 5 & 0 & -j & 0 \\ 0 & 5 & 0 & j \end{bmatrix}$ and $\mathbf{C}_{N_{t_2}} = \begin{bmatrix} 0 & -7 & 3j & 0 \\ 7 & 0 & 0 & -3j \end{bmatrix}$ and the overall transmission matrix $\mathbf{X}$ of (4) becomes $\mathbf{X} = \left[\begin{array}{cccc|cccc} 5 & 0 & -j & 0 & 0 & -7 & 3j & 0 \\ 7 & 0 & 0 & -3j & 0 & 5 & 0 & j \end{array}\right]$. Likewise, for the case of $N_t = 6$, the available $N_t = 6$ transmit antennas are divided as $N_{t_1} = 2$ and $N_{t_2} = 4$. Therefore, due to $N_{t_1} = 2$, $\mathbf{C}_{N_{t_1}}$ corresponds to Alamouti's STBC (1) matrix, and due to $N_{t_2} = 4$, $\mathbf{C}_{N_{t_2}}$ corresponds to ABBA STBC matrix. Then, the transmission matrix $\mathbf{X}$ (4) of the ST-QSM scheme for the case of $N_t = 6$, $N_{t_1} = 2$ and $N_{t_2} = 4$ is obtained as

$$\mathbf{X} = \left[\begin{array}{cc|cccc} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} & x_{16} \\ -x_{14}^* & x_{13}^* & -x_{16}^* & x_{15}^* & -x_{12}^* & x_{11}^* \end{array}\right] \tag{7}$$

where $x_{11}, x_{12} \in \{s_{1_\Re}, js_{2_\Im}, s_{1_\Re} + js_{2_\Im}, 0\}$ and $x_{13}, x_{14}, x_{15}, x_{16} \in \{s_{2_\Re}, js_{1_\Im}, s_{2_\Re} + js_{1_\Im}, 0\}$.

C. Receiver Structure

Assume that $\mathbf{X}$ is transmitted over a wireless channel and the matrix of received signals $\mathbf{Y} \in \mathbb{C}^{2\times N_r}$ is formulated as

$$\mathbf{Y} = \mathbf{X}\mathbf{H} + \mathbf{N} \tag{8}$$

where $\mathbf{H} \in \mathbb{C}^{N_t\times N_r}$ is a complex wireless MIMO channel matrix and $\mathbf{N} \in \mathbb{C}^{2\times N_r}$ is additive white Gaussian noise (AWGN) 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 variances 1 and N_0, respectively.

The receiver is assumed to have perfect channel state information (P-CSI). The maximum likelihood (ML) detector is used to obtain the optimum BER performance for the ST-QSM scheme. The ML detector considers all possible realizations of the active antenna indices for $l_{1_\Re}$, $l_{1_\Im}$, $l_{2_\Re}$ and $l_{2_\Im}$ in their corresponding antenna groups and M-QAM constellation symbols s_1 and s_2 to jointly detect the antenna indices $\hat{l}_{1_\Re}$, $\hat{l}_{1_\Im}$, $\hat{l}_{2_\Re}$ and $\hat{l}_{2_\Im}$ along with the data symbols $\hat{s}_1$ and $\hat{s}_2$:

$$\left[\hat{s}_1, \hat{s}_2, \hat{l}_{1_\Re}, \hat{l}_{1_\Im}, \hat{l}_{2_\Re}, \hat{l}_{2_\Im}\right] = \underset{s_1, s_2, l_{1_\Re}, l_{1_\Im}, l_{2_\Re}, l_{2_\Im}}{\arg\min} \left\|\mathbf{Y} - \mathbf{X}\mathbf{H}\right\|_F^2 \tag{9}$$

where $\|\cdot\|_F$ is the Frobenious norm.

III. Performance Analysis of The ST-QSM System

In this section, the error performance of the ST-QSM system is analyzed and the ABEP of the system is given by considering union bounding technique [12] in case of the transmitted matrix $\mathbf{X}_k$ is erroneously detected as $\hat{\mathbf{X}}_l$ by the receiver:

$$P_b \approx \frac{1}{2^{2m}} \sum_{k=1}^{2m} \sum_{l=1}^{2m} \frac{P(\mathbf{X}_k \to \hat{\mathbf{X}}_l) e(\mathbf{X}_k, \hat{\mathbf{X}}_l)}{2m} \tag{10}$$

where $P(\mathbf{X}_k \to \hat{\mathbf{X}}_l)$ is the corresponding pairwise error probability (PEP) and $e(\mathbf{X}_k, \mathbf{X}_l)$ is the number of the bit errors. The conditional PEP (CPEP) of the ST-QSM is calculated from [12]

$$P(\mathbf{X}_k \to \hat{\mathbf{X}}_l | \mathbf{H}) = Q\left(\sqrt{\frac{\left\|(\mathbf{X}_k - \hat{\mathbf{X}}_l)\mathbf{H}\right\|_F^2}{2N_0}}\right) \tag{11}$$

where $Q(x)$ is the Q-function, which can also be expressed as $Q(x) = \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-x^2/\sin^2\theta\right) d\theta$, and in this case, CPEP can be rewritten as

$$P(\mathbf{X}_k \to \hat{\mathbf{X}}_l | \mathbf{H}) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \exp\left(\frac{\left\|(\mathbf{X}_k - \hat{\mathbf{X}}_l)\mathbf{H}\right\|_F^2}{4N_0 \sin^2\theta}\right) d\theta. \tag{12}$$

Then, unconditional PEP (UPEP) of the system is obtained as follows by averaging (12) considering the moment generating function (MGF) of $\Gamma = \left\|(\mathbf{X} - \hat{\mathbf{X}})\mathbf{H}\right\|_F^2$:

$$P\left(\mathbf{X}_k \to \hat{\mathbf{X}}_l\right) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \left(\frac{\sin^2\theta}{\sin^2\theta + \frac{c_{1_{k,l}}}{4N_0}}\right)^{N_r} \left(\frac{\sin^2\theta}{\sin^2\theta + \frac{c_{2_{k,l}}}{4N_0}}\right)^{N_r} d\theta \tag{13}$$

where $c_{1_{k,l}}$ and $c_{2_{k,l}}$ are the non-zero eigenvalues of the matrix $(\mathbf{X}_k - \hat{\mathbf{X}}_l)(\mathbf{X}_k - \hat{\mathbf{X}}_l)^H$. It has been observed that a diversity order of two is obtained due to special structure of $\mathbf{X}$. In case of $c_{1_{k,l}} = c_{2_{k,l}} = c_{k,l}$, the PEP of (13) simplifies to

$$P\left(\mathbf{X}_k \to \hat{\mathbf{X}}_l\right) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \left(\frac{\sin^2\theta}{\sin^2\theta + \frac{c_{k,l}}{4N_0}}\right)^{2N_r} d\theta \tag{14}$$

IV. Simulation Results

In this section, for 4, 6 and 8 transmit antennas and different spectral efficiency values, the theoretical BER performance of the ST-QSM scheme is analyzed and supported via Monte Carlo simulation results. For different MIMO configurations, the BER performance of the ST-QSM scheme is compared with the QSM [8], STBC-SM [4] and Alamouti's STBC [5] schemes. In the following, Gray mapping is applied to symbol constellations and the BER curves are depicted as a function of γ, where γ is the received signal to noise ratio (SNR) at each received antenna. We consider $N_r = 2$ in all cases, while a generalization is straightforward.

In Fig. 2, the ABEP of 4×2 ST-QSM with 4-QAM, 6×2 ST-QSM with 8-QAM and 8×2 ST-QSM with 4-QAM are calculated theoretically and compared with the results obtained from Monte Carlo simulations for 4, 6 and 6 bpcu spectral efficiencies, respectively. It can be clearly seen that at high SNR values, the computer simulations show consistency with the theoretical results.

In Fig. 3, the proposed 4×2 ST-QSM scheme with 4-QAM is compared with the 4×2 STBC-SM scheme with 8-QAM and the 2×2 Alamouti's STBC with 16-QAM for 4 bpcu spectral efficiency. The results show that the BER performance of the proposed ST-QSM scheme is considerably better than the reference MIMO structures.

In the Figs. 4 and 5, for 4×2 and 8×2 MIMO systems, the BER performance of the ST-QSM scheme with 16-QAM and 32-QAM is compared with the QSM scheme with 4-QAM and 8-QAM, respectively. In both Figs. 4 and 5, due to the transmit diversity gain, ST-QSM exhibits significantly better performance than the QSM scheme. As seen from both Figs. 4 and 5, by reducing the spectral efficiency, an even better performance can be obtained by ST-QSM, 4×2, 4-QAM and 8×2 ST-QSM, 4-QAM schemes.

Finally, in Fig. 6, the BER performance of ST-QSM scheme for a 6×2 MIMO system, where $N_{t_1} = 2$ and $N_{t_2} = 4$, is provided for 4-QAM, 8-QAM and 16-QAM to achieve 5, 6 and 7 bpcu spectral efficiencies, respectively.

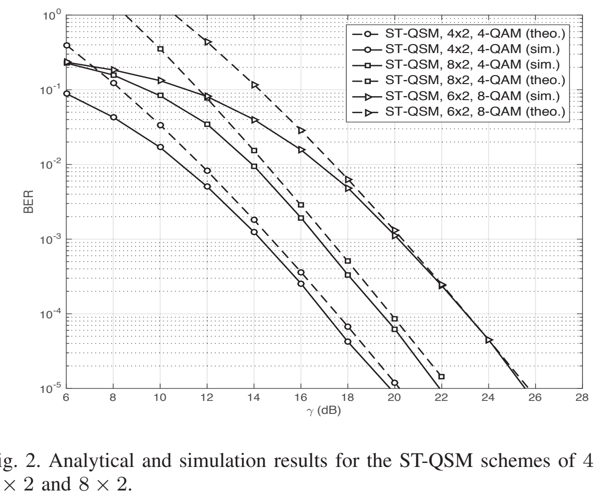

Fig. 2. Analytical and simulation results for the ST-QSM schemes of 4×2, 6×2 and 8×2.

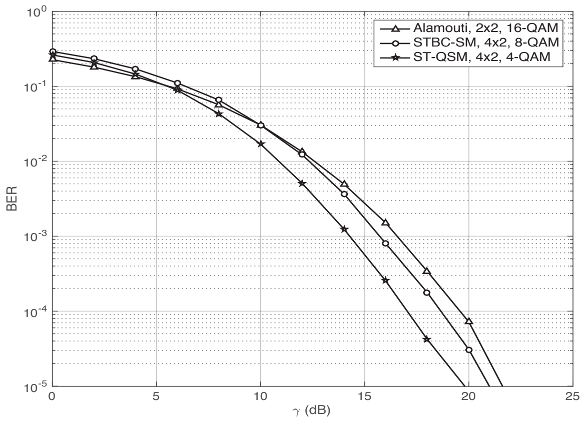

Fig. 3. Comparison of the BER performance of 4×2 ST-QSM with STBC-SM and 2×2 Alamouti STBC systems for $m = 4$ bpcu spectral efficiency.

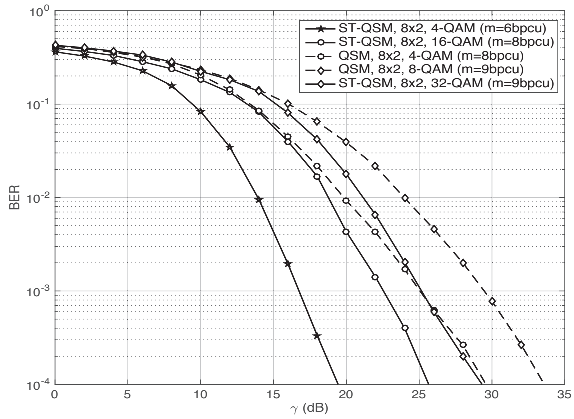

Fig. 5. Comparison of the BER performance of 8×2 ST-QSM and QSM schemes for $m = 6$, 8 and 9 bpcu spectral efficiencies.

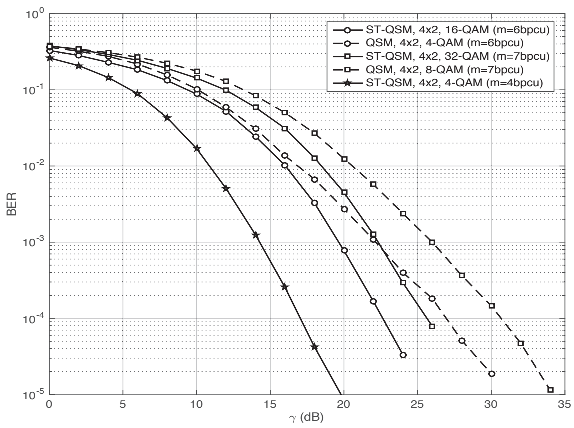

Fig. 4. Comparison of the BER performance of 4×2 ST-QSM and QSM schemes for $m = 4$, 6 and 7 bpcu spectral efficiencies.

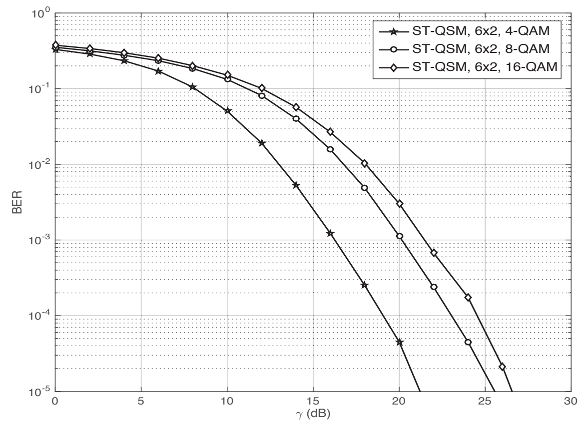

Fig. 6. BER performance of 6×2 ST-QSM scheme for $m = 5$, 6 and 7 bpcu spectral efficiencies.

V. Conclusion

In this paper, a novel high-rate MIMO transmission scheme, called ST-QSM, has been proposed. The ST-QSM technique combines the QSM scheme with the STBCs in order to take advantage of transmit diversity gain. In the ST-QSM scheme, the available transmit antennas have been subdivided into two groups and the information has been carried separately by the indices of the antennas in these groups as well as two complex M-QAM symbols. In this paper, for different MIMO configurations, the theoretical BER performance of the ST-QSM scheme has been obtained and confirmed via Monte Carlo simulations. It has also been shown by the extensive computer simulations that for the same spectral efficiency, the proposed ST-QSM scheme shows considerably better error performance than QSM, STBC-SM and Alamouti's STBC schemes.

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