Adaptive Space-Time Block Coded Spatial Modulation Algorithm Based on Constellation Transformation

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Abstract —In this paper, an Adaptive Space-Time Block Coded Spatial Modulation (ASTBC-SM) algorithm is proposed to improve the system performance under fixed spectral efficiency. The proposed scheme dynamically changes the scaling factor and rotation angle of the constellation used in each codebook according to the known Channel State Information (CSI). The coding gain of Space-Time Block Coded Spatial Modulation (STBC-SM) is also considered to further improve the performance of Bit Error Rate (BER). Moreover, in order to reduce the complexity of ASTBC-SM, a simplified algorithm which takes advantage of the orthogonality of Space-Time Block Coded (STBC) is also proposed. Performance analysis and simulation results show that the proposed ASTBC-SM algorithm can obtain better BER performance compared to traditional STBC-SM algorithm with low computational complexity and small feedback.

Index Terms—Adaptive spatial modulation, space-time block coded, constellation transformation, channel state information

I. Introduction

As a new Multiple-Input Multiple-Output (MIMO) technology, Spatial Modulation (SM) has attracted considerable attention in wireless communication since it was proposed [1], [2]. In SM, each time slot only activates one antenna for transmitting data. The special structure not only make SM avoid from Inter-Channel Interference (ICI) and the Inter-Antenna Synchronization (IAS), but also can make SM support more flexible antenna configuration [3], [4].

But the traditional SM does not exploit its potential for transmit diversity. In order to overcome this problem, Basar *et al.* recently proposed a Space-Time Block Coded Spatial Modulation (STBC-SM) technology [5]. As a very promising MIMO scheme, the design of STBC-SM makes full use of the advantages of SM and Space-Time Block Coded (STBC). Alamouti STBC is transmitted by two activate antennas in two symbol intervals. Both STBC symbols and the activate antenna pair carry information. In [6], [7], two algorithms were proposed to reduce the computational complexity of STBC-SM. By using the orthogonality of Alamouti STBC, the proposed algorithms can greatly reduce the computational complexity, while achieving approximate Maximum Likelihood (ML) error performance. Thus, they make the practical application of STBC-SM easier.

At present, the researches about STBC-SM have mostly focused on how to improve the spectral efficiency, such as the space-time block coded spatial modulation with cyclic structure (STBC-CSM) and the Spatial Modulation Orthogonal Space-Time Block Coded (SM-OSTBC) [8], [9]. In [10], the authors also have provided some guidelines for the design of high-rate STBC-SM with transmit-diversity equal to two and low decoding complexity. But few researchers have paid attention to how to improve the Bit Error Rate (BER) performance of STBC-SM system. In order to improve the performance of SM, the adaptive spatial modulation (ASM) technology is proposed [11]. In ASM, the receiving end selects the optimal symbol modulation order for possible active antenna according to the channel state information (CSI). Theoretical analysis and simulation results show that it can effectively improve the BER performance of SM, but the algorithm is extremely complex. In order to reduce computational complexity of ASM, a candidate-reduction-based ASM (CR-ASM) is proposed [12], which can effectively reduce the search space by removing the candidates with low probability. In addition, the results in [13] show that the design parameters of spatial constellation also have a significant impact on system performance. Therefore, by using the adaptive mechanism and redesigning the spatial constellation, we propose an Adaptive Space-Time Block Coded Spatial Modulation (ASTBC-SM) algorithm in this paper. The aim of this algorithm is to improve the BER performance of STBC-SM by combining the above two methods.

In the proposed ASTBC-SM algorithm, the transmitter selects dynamically the used constellation rotation angle and scaling factor for each codebook according to the channel state information, so as to improve the Bit Error Rate (BER) performance of STBC-SM. Firstly, at the sending and receiving end, we preset multiple different constellation rotation angle and scale factor combinations, then use the maximum received minimum distance criterion to choose the optimal combination under the given channel condition. At the end, the selected combination index is fed back to the sending end to prepare for the next data transmission. The analysis also

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shows that the constellation transformation can further increase the encoding gain of STBC-SM. In addition, in order to make the calculation of the ASTBC-SM algorithm simpler, we will use the orthogonality of STBC to simplify the selection algorithm in this paper.

II. System Model

Considering a STBC-SM system with N_T transmit antennas and N_R receive antennas, the transmitter architecture is shown in Fig. 1. In STBC-SM, the information bits to be transmitted are first divided into two parts, one part for selecting transmit antenna pair, and the other part for modulation of MPSK/M-QAM, to get two modulation symbols x_1, x_2 . Then x_1, x_2 are constructed as a code matrix $\mathbf{C}$ according to Alamouti scheme

$$\mathbf{C} = \begin{pmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{pmatrix} \tag{1}$$

where the row of matrix corresponds to the transmission time slot and the column of matrix corresponds to the transmit antenna. In the first transmission time slot, x_1, x_2 are respectively transmitted by two active transmit antennas, and $-x_2^*, x_1^*$ are transmitted by the same transmit antenna pair in second time slot.

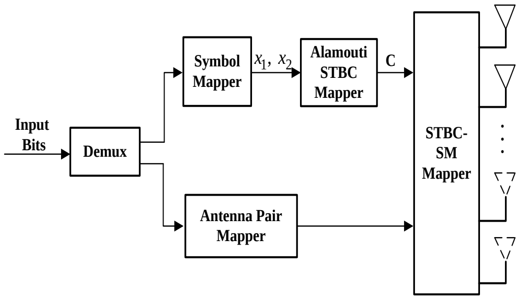

Fig. 1. Transmitter structure of the STBC-SM

The detailed design scheme of STBC-SM is given in [5]. For example of $N_T = 4$, there are two different codebooks $\boldsymbol{\chi}_1, \boldsymbol{\chi}_2$, which can be denoted as

$$\begin{aligned} \boldsymbol{\chi}_1 &= \left\{ \begin{bmatrix} x_1 & x_2 & 0 & 0 \\ -x_2^* & x_1^* & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & x_1 & x_2 \\ 0 & 0 & -x_2^* & x_1^* \end{bmatrix} \right\} \\ \boldsymbol{\chi}_2 &= \left\{ \begin{bmatrix} 0 & x_1 & x_2 & 0 \\ 0 & -x_2^* & x_1^* & 0 \end{bmatrix} \begin{bmatrix} x_2 & 0 & 0 & x_1 \\ x_1^* & 0 & 0 & -x_2^* \end{bmatrix} \right\} e^{j\phi} \end{aligned} \tag{2}$$

where each codebook has two different codewords $\mathbf{X}_{i,j}, j=1, 2$, and the codewords in the same codebook do not have overlapping non-zero column, ϕ is a rotation angle, which can be optimized for a given modulation format to ensure maximum diversity and coding gain.

It is assumed that the $2 \times N_T$ codeword $\mathbf{X}$ is transmitted over a $N_T \times N_R$ quasi-static Rayleigh flat fading MIMO channel $\mathbf{H}$, which remains constant in two consecutive symbol intervals. The received $2 \times N_R$ signal matrix can be denoted as

$$\mathbf{Y} = \sqrt{\rho}\mathbf{XH} + \mathbf{N} \tag{3}$$

where ρ is the average SNR at the each receive antenna, and $\mathbf{N}$ denotes $2 \times N_R$ noise matrix. The entries of both $\mathbf{H}$ and $\mathbf{N}$ are assumed to be independent and identically disturbed complex Gaussian random variables with zero mean and unit variance.

III. Proposed Adaptive Space-Time Block Coded Spatial Modulation Algorithm

A. Algorithm Description

In ASM, the modulation orders of transmit antennas are chosen according to the channel state information (CSI), and different active antennas may correspond to different modulation orders. The adaptive mechanism can reduce the possibility that receiver incorrectly detects the transmitted modulation symbols, so as to improve the BER performance of SM. But this scheme has a very obvious drawback: since the different active antennas transmitting modulation symbols may use different modulation orders, the number of information bits between transmitted and actually received is unequal if the active antenna is erroneously detected at receiving end. In this case, even if the subsequent detection is correct, it still leads to serious error propagation phenomenon because of the misalignment of bits.

To avoid the occurrence of this situation, in this paper, the proposed ASTBC-SM scheme will still use the same modulation orders for different active antenna pairs. Moreover, in order to maximize the minimum Euclidean distance of equivalent constellation, the traditional MPSK constellations will be scaled and rotated. In contrast to conventional STBC-SM scheme, symbol modulation will use the constellations which have been scaled and rotated in ASTBC-SM, and choose a different constellation rotation angle and scaling factor for each codebook according the change of channel conditions.

For convenience of express, we define a constellation scaling factor and rotation angle combination $\boldsymbol{\Psi}$

$$\boldsymbol{\Psi} = \{(r_1,\phi_1),(r_2,\phi_2),\ldots,(r_k,\phi_k)\} \tag{4}$$

where $0 \le \phi_i < \pi/2$, $r_i > 0$, $i=1, 2, ..., k$, k is the number of codebooks, and (r_i,ϕ_i) denotes the *ith* codebook's constellation scaling factor and rotation angle. Theoretically, since (r_i,ϕ_i) can be any value which meets power and angle constraint , $\boldsymbol{\Psi}$ has uncountable candidate combinations. The selection of combination $\boldsymbol{\Psi}$ will be analyzed in detail in the next section.

The STBC-SM system which has four transmit antenna is taken as an example. In this case, the codeword set consists of four different codewords and belongs to two different codebooks. Here, $\mathbf{\Psi}=\{(r_1,\phi_1),(r_2,\phi_2)\}$ and without loss of generality, $\phi_1=0,\ \phi_2=\phi$ are assumed. In order to ensure that the average transmission power is constant, r_1, r_2 should meet

$$r_1^2+r_2^2=2 \tag{5}$$

Assumed that ideal CSI is available at the receiver, for a given realization of the fading channel matrix $\mathbf{H}$, the pairwise error probability (PEP) of STBC-SM system with maximum likelihood (ML) detector is expressed as [14]

$$P(\mathbf{X}\to\hat{\mathbf{X}}\,|\,\mathbf{H})\approx\frac{1}{2}\lambda\cdot\exp\left(-\frac{1}{4N_0}d_{\min}^2(\mathbf{H})\right) \tag{6}$$

where λ is the average number of neighbor points and N_0 is the variance of noise, $d_{\min}(\mathbf{H})$ represents the received minimum distance which can be denoted as

$$d_{\min}=\min_{\mathbf{X}\neq\hat{\mathbf{X}}}\left\|(\mathbf{X}-\hat{\mathbf{X}})\mathbf{H}\right\|_F \tag{7}$$

where $\mathbf{X},\hat{\mathbf{X}}$ represent two different codeword matrices respectively, $\|\bullet\|_F$ stands for the Frobenius norm. In (7), the conditioned PEP is monotone decreasing function of the received minimum distance $d_{\min}(\mathbf{H})$. Therefore, we can improve the performance of system by maximizing the received minimum distance $d_{\min}(\mathbf{H})$. By using the orthogonality of STBC, (7) can be further simplified as

$$d_{\min}(\mathbf{H})=\min_{\substack{x_1,x_2,\hat{x}_1,\hat{x}_2\in\Omega\\ \ell,\partial=1,2,\ldots,I}}\left\|\mathbf{H}_\ell\begin{bmatrix}x_1\\x_2\end{bmatrix}-\mathbf{H}_\partial\begin{bmatrix}\hat{x}_1\\\hat{x}_2\end{bmatrix}\right\|_F \tag{8}$$

where Ω represents signal constellation, $x_i,\hat{x}_i\in\Omega$ denote the modulation symbol, $\mathbf{H}_\ell,\mathbf{H}_\partial$ denote the $2N_R\times 2$ equivalent channel matrix, I is the number of equivalent channel matrices. For $N_T=4$, there are four different codewords, corresponding to four different equivalent channel matrices, which can be expressed as

$$\mathbf{H}_1=r_1\begin{bmatrix}h_{1,1} & h_{1,2}\\ h_{1,2}^* & -h_{1,1}^*\\ h_{2,1} & h_{2,2}\\ h_{2,2}^* & -h_{2,1}^*\\ \vdots & \vdots\\ h_{N_R,1} & h_{N_R,2}\\ h_{N_R,2}^* & -h_{N_R,1}^*\end{bmatrix}\qquad \mathbf{H}_2=r_1\begin{bmatrix}h_{1,3} & h_{1,4}\\ h_{1,4}^* & -h_{1,3}^*\\ h_{2,3} & h_{2,4}\\ h_{2,4}^* & -h_{2,3}^*\\ \vdots & \vdots\\ h_{N_R,3} & h_{N_R,4}\\ h_{N_R,4}^* & -h_{N_R,3}^*\end{bmatrix}$$

$$\mathbf{H}_3=r_2\begin{bmatrix}h_{1,2}\varphi & h_{1,3}\varphi\\ h_{1,3}^*\varphi^* & -h_{1,2}^*\varphi^*\\ h_{2,2}\varphi & h_{2,3}\varphi\\ h_{2,3}^*\varphi^* & -h_{2,3}^*\varphi^*\\ \vdots & \vdots\\ h_{N_R,2}\varphi & h_{N_R,3}\varphi\\ h_{N_R,3}\varphi^* & -h_{N_R,2}\varphi^*\end{bmatrix}$$

$$\mathbf{H}_4=r_2\begin{bmatrix}h_{1,4}\varphi & h_{1,1}\varphi\\ h_{1,1}^*\varphi^* & -h_{1,4}^*\varphi^*\\ h_{2,4}\varphi & h_{2,1}\varphi\\ h_{2,1}^*\varphi^* & -h_{2,4}^*\varphi^*\\ \vdots & \vdots\\ h_{N_R,4}\varphi & h_{N_R,1}\varphi\\ h_{N_R,1}\varphi^* & -h_{N_R,4}\varphi^*\end{bmatrix} \tag{9}$$

where $h_{i,j}$ denotes channel gain between the ith receive antenna and the jth transmit antenna, r_1, r_2 are the scaling factor of constellations used for the corresponding codebook, $\varphi=e^{j\phi}$.

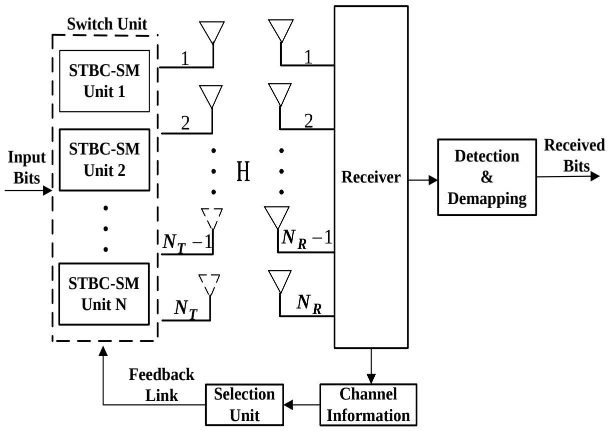

Fig. 2. Block diagram of the ASTBC-SM transceiver

The system model of the proposed ASTBC-SM is shown in Fig. 2. Firstly, N rotation angle and scaling factor combinations are preset in the sending and receiving ends. Then the receiver uses (8) to calculate the received minimum distance of the nth combination, and the criterion of maximizing the received minimum distance is used to choose the optimal combination which corresponds to the maximum $d_{\min}(\mathbf{H})$ from N different combinations. At the end, the combination index is fed back to the sending end, and makes transmitter change dynamically the chosen constellation rotation and scaling factor combination according to the feedback information so that ASTBC-SM system can obtain better BER performance. Table I shows that an alternative rotation angle and scaling factor combination set, where the used modulation scheme is QPSK.

TABLE I: ROTATION ANGLE AND SCALING FACTOR COMBINATION

Combination index	1st Codebook scaling factor	2nd Codebook scaling factor	Rotation angle
1	$\sqrt{0.49}$	$\sqrt{1.51}$	0.62
2	$\sqrt{0.81}$	$\sqrt{1.19}$	0.62
3	1	1	0.61
4	$\sqrt{0.51}$	$\sqrt{0.49}$	0.62

B. Parameter Selection

In this section, we focus on how to select rotation angle and scaling factor combinations. In [5], an important design parameter for quasi-static Rayleigh fading channels is the minimum coding gain distance (CGD), which is defined as

$$CGD_{\min}(\mathbf{X},\hat{\mathbf{X}}) = \min_{\mathbf{X}\neq\hat{\mathbf{X}}} \det(\mathbf{X}-\hat{\mathbf{X}})(\mathbf{X}-\hat{\mathbf{X}})^H \tag{10}$$

where $\mathbf{X}$ and $\hat{\mathbf{X}}$ are two different codewords, and $\mathbf{X}$ is transmitted and $\hat{\mathbf{X}}$ is erroneously detected. Since these codewords don't have identical non-zero column in the same codebook, namely they are mutually orthogonal and do not interfere with each other. The minimum CGD of the system depends on the minimum CGD between two codewords in the different codebooks. This is an important reason why we select different constellations in different codebooks in this paper. Without loss of generality, we assume that two different codewords are chosen as

$$\begin{aligned} \mathbf{X}_{1,k} &= \begin{pmatrix} x_1 & x_2 & 0 & 0_{1\times(n_T-3)} \\ -x_2^* & x_1^* & 0 & 0_{1\times(n_T-3)} \end{pmatrix} \\ \hat{\mathbf{X}}_{1,k} &= \begin{pmatrix} 0 & \hat{x}_1 & \hat{x}_2 & 0_{1\times(n_T-3)} \\ 0 & -\hat{x}_2^* & \hat{x}_1^* & 0_{1\times(n_T-3)} \end{pmatrix} e^{j\phi} \end{aligned} \tag{11}$$

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

$$\begin{aligned} &CGD_{\min}(\mathbf{X}_{1,k},\hat{\mathbf{X}}_{1,k}) = \min_{\mathbf{X}_{1,k},\hat{\mathbf{X}}_{1,k}} \{(\kappa - 2\Re\{\hat{x}_1^* x_2 e^{-j\phi}\}) \\ &(\kappa + 2\Re\{x_1 \hat{x}_2^* e^{j\phi}\}) - |x_1|^2|\hat{x}_1|^2 - |x_2|^2|\hat{x}_2|^2 + \\ &\Re\{x_1\hat{x}_1 x_2^* \hat{x}_2^* e^{j2\phi}\}\} \end{aligned} \tag{12}$$

where $\boldsymbol{\kappa} = \sum_{i=1}^{2}\left(|x_i|^2 + |\hat{x}_i|^2\right)$, ϕ denotes as rotation angle and can be optimized to obtain maximum diversity and code gain.

In order to obtain the minimum CGD of ASTBC-SM scheme, we put $x_1 = r_1 s_1$, $x_2 = r_2 s_2$, $\hat{x}_1 = r_1\hat{s}_1$, $\hat{x}_2 = r_2\hat{s}_2$ into formula (12) and can obtain the calculating formula as

$$\begin{aligned} &CGD_{\min}(\mathbf{X}_{1,k},\hat{\mathbf{X}}_{1,k}) = \min_{\mathbf{X}_{1,k},\hat{\mathbf{X}}_{1,k}} \{16 + 8r_1r_2\Re\{s_1\hat{s}_2^* e^{j\phi}\} - \\ &8r_1r_2\Re\{\hat{s}_1^* s_2 e^{-j\phi}\} + 4r_1^2r_2^2\Re\{s_1\hat{s}_2^* e^{j\phi}\}\Re\{\hat{s}_1^* s_2 e^{-j\phi}\} - \\ &2r_1^2r_2^2 + 2r_1^2r_2^2\Re\{s_1\hat{s}_1 s_2^*\hat{s}_2^* e^{j2\phi}\}\} \end{aligned} \tag{13}$$

where $s_i, \hat{s}_i$ from MPSK constellation, and the power of each modulation symbol is normalized, i.e. $|s_i|^2 = |\hat{s}_i|^2 = 1$. We can see from (13), the minimum CGD of ASTBC-SM is related to rotation angle and scaling factor.

For an illustrative propose, in Fig. 3, we plot a 3D graphic about the minimum CGD of ASTBC-SM according to (13), where $N_T = 4$ and QPSK modulation are used. It is observed that the minimum CGD can be improved by allocating appropriate scaling factor and rotation angle between different codewords. The conclusion also can be verified under different modulation levels by the same method. Therefore, compared with traditional STBC-SM algorithm, the ASTBC-SM algorithm can effectively improve the minimum CGD.

It can be seen from the Fig. 3 that the minimum CGD value will change along with the change of (r_1, ϕ). A very apparent trend in this figure is that the smaller r_1 is, the bigger minimum CGD is. But if r_1 is too small, it will lead to serious error in the symbol demodulation. In addition, through the substantial computer simulations for the BER performance of ASTBC-SM system when $\boldsymbol{\Psi}$ is different, we find the $\boldsymbol{\Psi}$ corresponding to very small r_1 will lead to relatively small received minimum distance for most channel realization. So this combination is almost can not be used in the sending end, and only further increases the computational complexity of ASTBC-SM algorithm. A large number of simulation experiments show that the reasonable range of r_1 should be approximately set as 0.6~1.

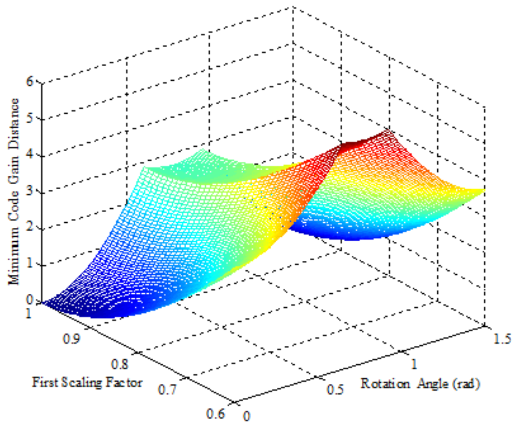

Fig. 3. Minimum CGD of STBC-SM with respect to r_1 and ϕ, where $N_T = 4$ and QPSK modulation are considered.

TABLE II: THE VALUE OF $CGD_{\min}$ WITH DIFFERENT ROTATION ANGLES AND SCALING FACTORS

Modulation scheme	1st Codebook scaling factor	Rotation angle	Minimum CGD
BPSK	0.8	1.34	12.52
	0.9	1.34	12.14
	1	1.57	12
QPSK	0.8	0.62	3.85
	0.9	0.62	3.12
	1	0.61	2.86
8PSK	0.8	0.30	1.75
	0.9	0.48	0.98
	1	0.48	0.69

Table II gives several suitable rotation angle and scaling factor combinations and the corresponding minimum CGD, where different modulation levels are considered and rotation angles are optimal under current scaling factors and modulation levels. It should be noted that the minimum CGD corresponding to $r_1=1$ is also the minimum CGD of classical STBC-SM. As can be seen from the table, the minimum CGD of STBC-SM has been effectively improved by rotating and scaling the MPSK constellation.

IV. Simplified Adaptive Space-Time Block Coded Spatial Modulation Algorithm

As can be seen that the ASTBC-SM algorithm is very complicated from (8), to overcome this problem, this paper will use the orthogonality of STBC to reduce the complexity of the adaptive algorithm, where $\mathbf{x}=\begin{bmatrix}x_1 & x_2\end{bmatrix}^T$ denotes modulation symbols pair. And without loss of generality, the power of each modulation symbol is assumed to be normalized, i.e. $|x_k|^2=1$. The calculation of received minimum distance for each combination can be divided into the following three cases:

Case 1: $\mathbf{H}_\ell=\mathbf{H}_\partial$, $\mathbf{x}\neq\hat{\mathbf{x}}$, the received minimum distance can be written as

$$\begin{aligned} d_{\min,1}(\mathbf{H}) &= \min_{\substack{\mathbf{x}\neq\hat{\mathbf{x}}\\ \ell,\partial=1,2,\ldots,I}} \left\|\mathbf{H}_\ell\mathbf{x}-\mathbf{H}_\partial\hat{\mathbf{x}}\right\|_F \\ &= \min_{\substack{\mathbf{x}\neq\hat{\mathbf{x}}\\ \ell=1,2,\ldots,I}} \left\|\mathbf{H}_\ell(\mathbf{x}-\hat{\mathbf{x}})\right\|_F \end{aligned} \tag{14}$$

According to the properties of vector norm, (14) is equal to

$$\left\|\mathbf{H}_\ell(\mathbf{x}-\hat{\mathbf{x}})\right\|_F=\sqrt{(\mathbf{x}-\hat{\mathbf{x}})^H\mathbf{H}_\ell^H\mathbf{H}_\ell(\mathbf{x}-\hat{\mathbf{x}})} \tag{15}$$

Due to the orthogonality of STBC, it is easy to verify

$$\mathbf{H}_\ell^H\mathbf{H}_\ell=\sum_{i=1}^{2N_R}\left|h_{i,1}^\ell\right|^2\mathbf{I}_2=m_{\ell,1}\mathbf{I}_2 \tag{16}$$

where $h_{i,1}^\ell$ is the element corresponding to the ith row and the first column of the equivalent channel matrix $\mathbf{H}_\ell$, $m_{\ell,1}$ denotes the inner product of first column of $\mathbf{H}_\ell$, and $m_{\ell,1}=m_{\partial,1}$, $\mathbf{I}_2$ is a 2×2 identity matrix. $(\mathbf{x}-\hat{\mathbf{x}})^H\mathbf{H}_\ell^H\mathbf{H}_\ell(\mathbf{x}-\hat{\mathbf{x}})$ can be simplified to

$$\begin{aligned} (\mathbf{x}-\hat{\mathbf{x}})^H\mathbf{H}_\ell^H\mathbf{H}_\ell(\mathbf{x}-\hat{\mathbf{x}}) &= m_{\ell,1}(\mathbf{x}-\hat{\mathbf{x}})^H(\mathbf{x}-\hat{\mathbf{x}}) \\ &= m_{\ell,1}\sum_{k=1}^{2}\left|x_k-\hat{x}_k\right|^2 \end{aligned} \tag{17}$$

For MPSK modulation, $\min_{\mathbf{x}\neq\hat{\mathbf{x}}}\sum_{i=1}^{2}\left|x_k-\hat{x}_k\right|^2$ is a constant, and can be denoted as

$$\min_{\mathbf{x}\neq\hat{\mathbf{x}}}\sum_{i=1}^{2}\left|x_k-\hat{x}_k\right|^2=4\sin^2(\frac{\pi}{M}) \tag{18}$$

So in the first case, the received minimum distance can be expressed as

$$\begin{aligned} d_{\min,1}(\mathbf{H}) &= \min_{\mathbf{x}\neq\hat{\mathbf{x}}}\sqrt{m_{\ell,1}\sum_{k=1}^{2}|x_k-\hat{x}_k|^2} \\ &= \min_{\ell=1,2,\ldots,I} 2\sin(\frac{\pi}{M})\sqrt{m_{\ell,1}} \end{aligned} \tag{19}$$

Case 2: $\mathbf{H}_\ell\neq\mathbf{H}_\partial$, $\mathbf{x}=\hat{\mathbf{x}}$, the received minimum distance can be written as

$$d_{\min,2}=\min_{\mathbf{H}_\ell\neq\mathbf{H}_\partial}\left\|\mathbf{H}(\mathbf{x}-\hat{\mathbf{x}})\right\|_F=\min_{\mathbf{H}_\ell\neq\mathbf{H}_\partial}\left\|(\mathbf{H}_\ell-\mathbf{H}_\partial)\mathbf{x}\right\|_F \tag{20}$$

As in the first case, the above formula can be written as

$$\left\|(\mathbf{H}_\ell-\mathbf{H}_\partial)\mathbf{x}\right\|_F=\sqrt{\mathbf{x}^H(\mathbf{H}_\ell-\mathbf{H}_\partial)^H(\mathbf{H}_\ell-\mathbf{H}_\partial)\mathbf{x}} \tag{21}$$

where $(\mathbf{H}_\ell-\mathbf{H}_\partial)^H(\mathbf{H}_\ell-\mathbf{H}_\partial)$ is equal to

$$\begin{aligned} (\mathbf{H}_\ell-\mathbf{H}_\partial)^H(\mathbf{H}_\ell-\mathbf{H}_\partial) &= \sum_{i=1}^{2N_R}(|h_{i,1}^\ell-h_{i,1}^\partial|^2)\mathbf{I}_2 \\ &= (m_{\ell,1}+m_{\partial,1}-2\Re(m_{\ell\partial,1}))\mathbf{I}_2 \end{aligned} \tag{22}$$

It follows that

$$\begin{aligned} &\mathbf{x}^H(\mathbf{H}_\ell-\mathbf{H}_\partial)^H(\mathbf{H}_\ell-\mathbf{H}_\partial)\mathbf{x} = (m_{\ell,1}+m_{\partial,1}- \\ &2\Re(m_{\ell\partial,1})\mathbf{x}^H\mathbf{x} \end{aligned} \tag{23}$$

where $m_{\ell\partial,1}$ is the inner product between the first column of $\mathbf{H}_\ell$ and $\mathbf{H}_\partial$, and $\mathbf{x}^H\mathbf{x}=2$, So in the second case, the received minimum distance can be written as

$$d_{\min,2}(\mathbf{H})=\min_{\substack{\ell,\partial=1,2,\ldots I\\ \ell\neq\partial}}\sqrt{2(m_{\ell,1}+m_{\partial,1}-2\Re(m_{\ell\partial,1}))} \tag{24}$$

Case 3: $\mathbf{H}_\ell\neq\mathbf{H}_\partial$, $\mathbf{x}\neq\hat{\mathbf{x}}$, In this case, the received minimum distance can be written as

$$d_{\min,3}(\mathbf{H})=\min_{\substack{\mathbf{x}\neq\hat{\mathbf{x}}\\ \mathbf{H}_\ell\neq\mathbf{H}_\partial}}\left\|\mathbf{H}(\mathbf{x}-\hat{\mathbf{x}})\right\|_F=\min_{\substack{\mathbf{x}\neq\hat{\mathbf{x}}\\ \mathbf{H}_\ell\neq\mathbf{H}_\partial}}\left\|\mathbf{H}_\ell\mathbf{x}-\mathbf{H}_\partial\hat{\mathbf{x}}\right\|_F \tag{25}$$

Likewise, $\left\|\mathbf{H}_\ell\mathbf{x}-\mathbf{H}_\partial\hat{\mathbf{x}}\right\|_F$ is equal to

$$\begin{aligned} \left\|\mathbf{H}_\ell\mathbf{x}-\mathbf{H}_\partial\hat{\mathbf{x}}\right\|_\mathbf{F} &= \sqrt{\begin{array}{l}\mathbf{x}^H\mathbf{H}_\ell^H\mathbf{H}_\ell\mathbf{x}+\hat{\mathbf{x}}^H\mathbf{H}_\partial^H\mathbf{H}_\partial\hat{\mathbf{x}}\\ -\mathbf{2}\Re(\mathbf{x}^H\mathbf{H}_\ell^H\mathbf{H}_\partial\hat{\mathbf{x}})\end{array}} \\ &= \sqrt{\begin{array}{l}2m_{\ell,1}+2m_{\partial,1}-2\Re(m_{\ell\partial,1}x_1^*\hat{x}_1+(m_{\ell\partial,1})^*\\ x_2^*\hat{x}_2+(m_{\partial1,\ell2})x_1^*\hat{x}_2-(m_{\partial1,\ell2})^*x_2^*\hat{x}_1)\end{array}} \end{aligned} \tag{26}$$

After obtaining the $d_{\min}(\mathbf{H})$ of different situations, the received minimum distance for the nth rotation angle and scaling factor combination can be expressed as

$$d_{\min}^n(\mathbf{H})=\min(d_{\min,1}^n(\mathbf{H}),d_{\min,2}^n(\mathbf{H}),d_{\min,3}^n(\mathbf{H})) \tag{27}$$

As can be seen from the above analysis, in the first and second cases, the computation of the received minimum distance becomes very simple, and in the third case, it is somewhat complex. In order to further simplify the calculation of the received minimum distance, for a given realization of $\mathbf{H}$, we can firstly calculate the column inner product value of equivalent channel matrix used in (19), (24) and (26). Although different combinations will produce different equivalent channel matrices, the difference between them is just a constant. The number of combinations is N, but the inner product of equivalent channel matrices is computed only once. Compared to the formula (8), after these treatments, the computation of received minimum distance can be greatly simplified.

V. Comparison of Computational Complexity

In this section, the computational complexity of the propose algorithms is evaluated and compared. Here, the computational complexity is evaluated in terms of the number of complex additions and multiplications.

Firstly, we evaluate the computational complexity of the proposed ASTBC-SM algorithm according to (8). For each scaling factor and rotation angle combination, the computation of the received minimum distance requires $5N_R(C^2M^4 - CM^2)$ complex multiplications and $3N_R(C^2M^4 - CM^2)$ complex additions. Therefore, the computational complexity imposed by the proposed ASTBC-SM algorithm is given by

$$\delta_{ASTBC-SM} = 8NN_R(C^2M^4 - CM^2) \tag{28}$$

where N is the number of scaling factor and rotation angle combinations, and $C = 2^{\lfloor \log_2 C_{N_T}^2 \rfloor}$ is the number of codewords, equaling to the number of equivalent channel matrices.

Next, we evaluate the computational complexity of the proposed simplified ASTBC-SM algorithm in stages. The computation of the complexity can be divided into two steps in the simplified ASTBC-SM algorithm. Firstly, computing the column inner product value of the equivalent channel matrices used in (19), (24) and (26) requires $(N_RC^2 + N_RC)$ complex multiplications and $(2N_R - 1)(C^2 - C)/2$ complex additions. It should be noted that the inner product value of the equivalent channel matrices will be stored and be used in computing the received minimum distance of different candidate combinations. Secondly, the rest of (19), (24) and (26) require $4C(C-1)M^2(M^2-1)$ complex multiplications and $C(C-1) + 5C(C-1)M^2(M^2-1)/2$ complex additions. Hence, the computational complexity imposed by the simplified ASTBC-SM algorithm is given by

$$\begin{aligned}\delta_{Simplified} = 2N_RC^2 - (C^2 - C)/2 + N(C^2 - C + \\ 13(C^2 - C)(M^4 - M^2)/2)\end{aligned} \tag{29}$$

Table III gives the computational complexity of the proposed algorithms under different conditions. As we can see from the table, the simplified ASTBC-SM algorithm significantly reduces the computational complexity of ASTBC-SM algorithm. When $N = 2$, for a 4×4 QPSK STBC-SM system, the ASTBC-SM algorithm requires 258048 complex additions and multiplications, while the simplified ASTBC-SM algorithm only requires 37586. This represents a 85% reduction in computational complexity.

TABLE III: COMPARISON OF COMPUTATIONAL COMPLEXITY BETWEEN THE PROPOSED ASTBC-SM AND SIMPLIFIED ASTBC-SM ALGORITHM

Configuration	ASTBC-SM	Simplified ASTBC-SM
$N_T = N_R = 4$, $M = 4$, $N = 2$	258048	37586
$N_T = N_R = 4$, $M = 4$, $N = 4$	516096	75050
$N_T = N_R = 4$, $M = 8$, $N = 4$	6192456	1258154

VI. Simulation Results

In order to verify the effectiveness of proposed algorithm, the BER performance of the proposed ASTBC-SM algorithm and the traditional algorithm are compared by computer simulation. In all simulations, the channel model is assumed to be quasi Rayleigh flat fading channel, and the channel state information is perfectly known at the receiver. Moreover, the feedback channel delay is zero and simulation environment is set to $N_T = N_R = 4$. The performance of algorithms are simulated and verified under spectral efficiency $4\text{bit}/(\text{s}\cdot\text{Hz})$, $6\text{bit}/(\text{s}\cdot\text{Hz})$ and $8\text{bit}/(\text{s}\cdot\text{Hz})$.

Fig. 4 shows the BER performance curves of two algorithms, and it is evident that the ASTBC-SM algorithm outperforms traditional STBC-SM algorithm. A performance gain of approximately 2dB is achieved at a BER of 10^{-5}, and with the increase of SNR, the advantage of the proposed algorithm in improving performance will become more obvious.

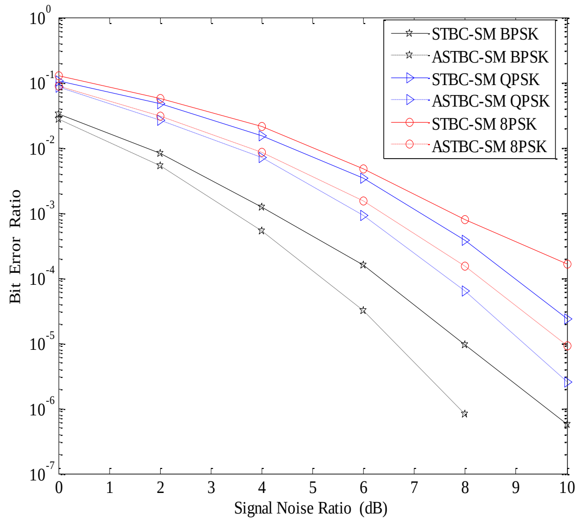

Fig. 4. BER performance comparison with different modulation schemes

Fig. 5 presents the BER performance curves of the proposed algorithm within different number of alternative combinations under QPSK. As can be seen from Fig.5, the performance of the proposed algorithm can be further improved with the increase of the number of alternative combinations. With the number of alternative combinations of 2, 4, 8, the performance can be increased by 1dB, 2dB and 2.5dB, respectively, the corresponding feedback overhead is 1, 2, 3 bits. But the simulation results also show that the improvement of BER performance will be smaller and smaller with the continued increase of combination number. On the contrary, it will increase feedback overhead, so we should do compromise between the performance and the amount of feedback according to the specific situation.

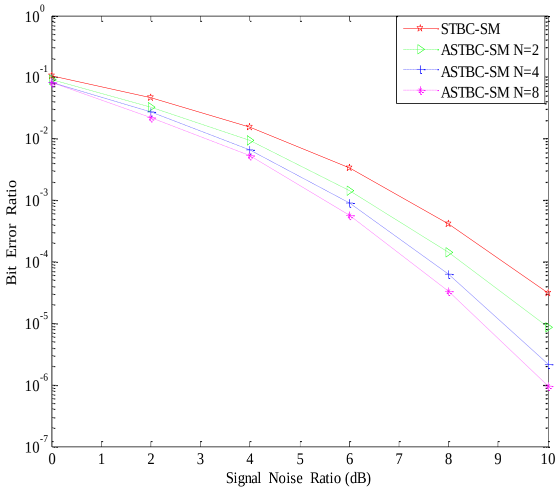

Fig. 5. BER performance of the proposed ASTBC-SM with different combinations.

VII. Conclusions

In order to improve the BER performance of STBC-SM by using the channel state information, the adaptive STBC-SM scheme is proposed in this paper. The algorithm can dynamically change the constellation rotation angle and scaling factor used in each codebook according to the channel condition. The coding gain will also be taken into account when selecting from the candidate constellation rotation angle and scaling factor combinations, so that the system performance can be further improved. In addition, since the ASTBC-SM algorithm has higher computational complexity, a simplified algorithm is also proposed to reduce the complexity of ASTBC-SM algorithm by using the orthogonality of STBC, which is valuable for practical application of ASTBC-SM algorithm in the future.

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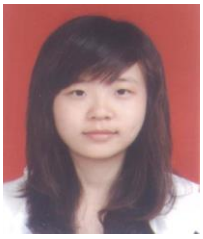

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