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PERFORMANCE ANALYSIS OF STBC SPATIAL MODULATION UNDER TRANSMIT DIVERSITY AND MULTIPLEXING GAIN

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Abstract

Performance analysis for spatial modulation MIMO system was investigated. To deal with the transmit diversity gain and multiplexing gain parallel ,we have proposed a Spatial Modulation scheme cascaded with STBC-SM and OSTBC-SM ,From STBC code we can achieve Transmit diversity and from spatial modulation we can achieve multiplexing gain, with MRC detection algorithm models has BER analysis compared with basics Almouti code and STBC-SM and OSTBC-SM.

Keywords— MRC, OSTBC, SM, Alamouti code

Introduction

Multiple–antenna techniques constitute a key technology for modern wireless communications, which trade–off superior error performance and higher data rates for increased system complexity and cost. Among the many transmission principles that exploit multiple–antenna either at the transmitter, the receiver, or both, Spatial Modulation (SM) is a novel and recently proposed multiple– antenna transmission technique which can offer, with a very low system complexity, improved data rates compared to Single–Input–Single–Output (SISO) systems, and robust error performance even. Spatial modulation (SM) is a recently developed transmission technique that uses multiple antennas. The basic idea is to map a block of information bits to two information carrying units: 1) a symbol that was chosen from a constellation diagram and 2) a unique transmit antenna number that was chosen from a set of transmit antennas. The use of the transmit antenna number as an information-bearing unit increases the overall spectral efficiency by the base-two logarithm of the number of transmit antennas. At the receiver, a maximum receive ratio combining algorithm is used to retrieve the transmitted block of information bits [1].

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It combines spatial modulation (SM) and space-time block coding (STBC) to take advantage of the benefits of both while avoiding their drawbacks. SM can achieve a higher capacity than multiple–antenna schemes with similar decoding complexity, such as Space–Time Block Codes (STBCs), along with a smaller bit error probability than Vertical Bell Laboratories Layered Space–Time (V–BLAST) and Alamouti schemes [2].

Space modulation is a novel digital modulation concept for Multiple–Input–Multiple–Output (MIMO) wireless systems, which is receiving a growing attention due to the possibility of realizing low–complexity and spectrally–efficient MIMO implementations[3]–[4]. Spatial Modulation (SM) [5], and Space Shift Keying (SSK) modulation [6]. Although different from one another, all these transmission technologies share the same fundamental working principle, which makes them different from conventional modulation schemes: they encode part of the information bits into the spatial position of the antenna–array, which plays the role of a constellation diagram (the so–called "spatial–constellation diagram") for data modulation [4]. In SSK modulation, blocks of information bits are mapped into the index of a single transmit–antenna, which is switched on for data transmission while all the other antennas radiate no power [6]. In SSK modulation, regardless of the number of simultaneously–active antennas at the transmitter, SSK modulation is unable to provide transmit–diversity gains

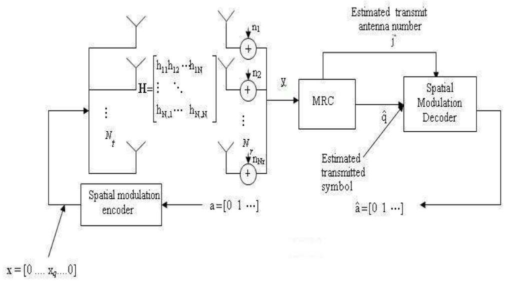

Fig.1 Spatial modulation scheme

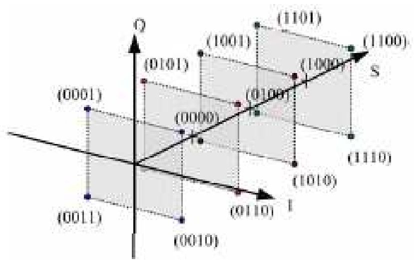

Fig.2 Principal of SM

Spatial modulation (SM) technique proposed by Mesleh can overcome the above problems. SM is an extension of conventional modulation, and the constellation with 3 dimensions is constructed. Take QPSK modulation with 4 transmit antennas as an example, 4 bits are mapped to a symbol. The first 2 bits are used to choose transmit antenna, and the last 2 bits are used for the conventional QPSK modulation, as shown in Fig.2. For SM system, only one antenna is activated to carry useful data at any time, and others are silent, therefore ICI can be avoid. Which antenna is activated is decided by the input data, so the index of antenna can be used to carry some useful information, and the spectral efficiency will be increased [7].

Space-Time Block Coded Spatial Modulation (STBC-SM)

In the STBC-SM scheme [8], shown in Figure (2), both STBC symbols and the indices of the transmit antennas from which these symbols are transmitted, carry information. It chooses Alamouti's STBC as the core STBC due to its advantages in terms of spectral efficiency and simplified ML detection. During each two consecutive symbol intervals, $2m$ 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, where the first $\log 2c$ bits determine the antenna-pair position $l = u_1 2^{\log 2c-1} + u 2^{\log 2c-2} + \ldots + u \log_2 c 2^0$ that is associated with the corresponding antenna pair, while the last $2\log_2 M$ bits determine the symbol pair $(x_1, x_2) \in \gamma^2$. The spectral efficiency of the STBC-SM scheme is larger than that of Alamouti's scheme by an amount of $(1/2\log_2 c)$ bits/s/Hz provided by the antenna modulation.

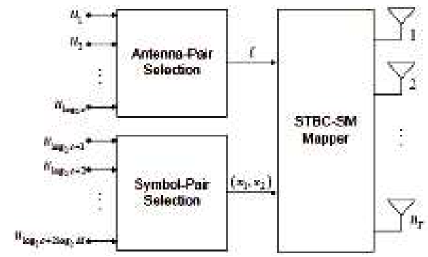

Fig.3. The block diagram of the STBC-SM transmitter

A MIMO system STBC SM with four transmit antenna that transmit the Alamouti STBC can be expressed by one of the following four codewords [8],

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

$$x_2 = \{x_{21}, x_{22}\} = \left\{ \begin{pmatrix} 0 & x_1 & x_2 & 0 \\ 0 & -x_2^* & x_1^* & 0 \end{pmatrix} \begin{pmatrix} x_2 & 0 & 0 & x_1 \\ x_1^* & 0 & 0 & -x_2^* \end{pmatrix} \right\} . e^{j\theta}$$

where $\chi_i = 1,2$ are called the STBC-SM codebooks each containing two STBC-SM code words , X_{ij}, j=1,2 , which do not interfere to each other. θ is a rotation angle to be optimized for a given modulation format to ensure maximum diversity and coding gain at the expense of expansion of the signal constellation. However, if θ is not considered, overlapping columns of codeword pairs from different codebooks would reduce the transmit diversity order to one [8].

Alamouti Code

Historically, the Alamouti code is the first STBC that provides full diversity at full data rate for two transmit antennas. A block diagram of the Alamouti space-time encoder is shown in Fig.4.

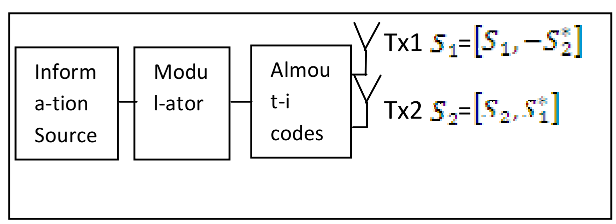

Fig.4 A block diagram of the Alamouti space-time encoder.

The information bits are first modulated using an M-ary modulation scheme. The encoder takes the block of two modulated symbols s_1 and s_2 in each encoding operation and hands it to the transmit antennas according to the code matrix

$$S = \begin{bmatrix} S_1 & S_2 \\ -S_2^* & S_1^* \end{bmatrix} \quad (1)$$

The first row represents the first transmission period and the second row the second transmission period. During the first transmission, the symbols s_1 and s_2 are transmitted simultaneously from antenna one and antenna two respectively. In the second transmission period, the symbol $-s^*_2$ is transmitted from antenna one and the symbol s^*_1 from transmit antenna two. It is clear that the encoding is performed in both time (two transmission intervals) and space domain (across two transmit antennas).

$$SS^H = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} s_1^* & -s_2 \\ s_2^* & s_1 \end{bmatrix}$$

$$= \begin{bmatrix} |s_1|^2 + |s_2|^2 & 0 \\ 0 & |s_1|^2 + |s_2|^2 \end{bmatrix} = (|s_1|^2 + |s_2|^2) I_2 \quad (2)$$

where I_2 is a (2×2) identity matrix. This property enables the receiver to detect s_1 and s_2 by a simple linear signal processing operation.

Let us look at the receiver side now. Only one receive antenna is assumed to be available. The channel at time t may be modeled by a complex multiplicative distortion $h_1(t)$ for transmit antenna one and $h_2(t)$ for transmit antenna two. Assuming that the fading is constant across two consecutive transmit periods of duration T, we can write

$$h_1(t) = h_1(t + T) = h_1 = |h_1| e^{j\theta_1}$$
$$h_2(t) = h_2(t + T) = h_2 = |h_2| e^{j\theta_2} \quad (3)$$

where $|h_i|$ and θ_i, i = 1, 2 are the amplitude gain and phase shift for the path from transmit antenna i to the receive antenna. The received signals at the time t and t + T can then be expressed as

$$r_1 = s_1 h_1 + s_2 h_2 + n_1$$
$$r_1 = -s_1^* h_1 + s_2^* h_2 + n_2 \quad (4)$$

where r_1 and r_2 are the received signals at time t and t + T, n_1 and n_2 are complex random variables representing receiver noise and interference. This can be written in matrix form as:

$$\mathbf{r = S\,h + n} \quad (5)$$

where h = [h_1, h_2]T is the complex channel vector and n is the noise vector at the receiver [9].

Orthogonal Space-Time Block Codes

The pioneering work of Alamouti is to create STBCs for more than two transmit antennas. First of all, Tarokh studied the error performance associated with unitary signal matrices. Sometime later, Ganesan at al. streamlined the derivations of many of the results associated with OSTBC and established an important link to the theory of the orthogonal and amicable orthogonal designs. Orthogonal STBCs are an important subclass of linear STBCs that guarantee that the ML detection of different symbols $\{s_n\}$ is decoupled and at the same time the transmission scheme achieves a diversity order equal to $n_t n_r$. The main disadvantage of OSTBCs is that for more than two transmit antennas and complex-valued signals, OSTBCs only exist for code rates smaller than one symbol per time slot. Next, we will give a general survey on orthogonal design and various properties of OSTBCs. There exist real orthogonal and complex orthogonal designs. We focus here on complex orthogonal designs. More about real orthogonal design can be found in [9].

A. Orthogonal Design

An OSTBC is a linear space-time block code S that has the following unitary property:

$$S^H S = \sum_{n=1}^{N} |S_n|^2 \mathbf{I} \quad (6)$$

The i-th row of S corresponds to the symbols transmitted from the i-th transmit antenna in N transmission periods, while the j-th column of S represents the symbols transmitted simultaneously through n_t transmit antennas at time j.

According to (6) the columns of the transmission matrix S are orthogonal to each other. That means that in each block, the signal sequences from any two transmit antennas are orthogonal. The orthogonality enables us to achieve full transmit diversity and at the same time, it allows the receiver by means of simple MRC to decouple the signals transmitted from different antennas and consequently, it allows a simple ML decoding.

Receiver Algorithm

A. Maximum Likelihood Equalizer

In statistics, maximum-likelihood estimation (MLE) is a method of estimating the parameters of a statistical model. When applied to a data set and given a statistical model, maximum-likelihood estimation provides estimates for the model's parameters. In general, for a fixed set of data and underlying statistical model, the method of maximum likelihood selects values of the model parameters that produce a distribution that gives the observed data the greatest probability Maximum-likelihood estimation gives a unified approach to estimation, which is well-defined in the case of the normal distribution and many other problems.

Suppose there is a sample x1, x2, …, xn of n independent and identically distributed observations, coming from a distribution with an unknown pdf $f0(\cdot)$. It is however surmised that the function $f0$ belongs to a certain family of distributions $\{ f(\cdot|\theta), \theta \in \Theta \}$, called the parametric model, so that $f0 = f(\cdot|\theta0)$. The value θ0 is unknown and is referred to as the "true value" of the parameter. It is desirable to find an estimator which would be as close to the true value θ0 as possible. Both the observed variables xi and the parameter θ can be vectors.

System model

SM is also a spatial multiplexing MIMO technology. It has N_T transmit antennas and N_R receive antennas, and the modulation order is M . Input data is converted into $\log_2 (MN_T)$ layers, then the transmit signal vector in one time slot, which is denoted by $\boldsymbol{x} = [x_1, x_2\ldots, x_N]^T$, can be obtained through SM mapping, and $E\{\boldsymbol{x}^H \boldsymbol{x}\} = 1$. In the receiver, SM detection includes 2 steps, the first is estimation of the index of transmit antenna, the second is symbol demodulation for this antenna. The system diagram is shown in Fig.2.

For SM system, only one antenna is activated to carry information at one time slot, the others are silent. So only one element of $\boldsymbol{x}$ is nonzero. Here we use $v = [v_1, v_2\ldots v_{NR}]$ to denote the complex Gaussian noise vector of N_R receive

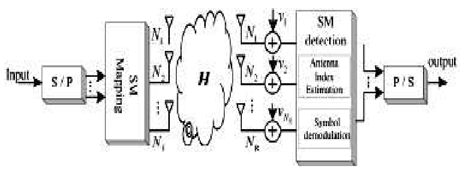

Fig.5 SM system diagram

Antennas, and $E\{v_i\} = 0$, $E\{ v^H v \} = \sigma_v^2$. Then received signal $y= [y_1, y_2\ldots y_{NR}]$ for N_R receive antennas at one time slot can be denoted by

$$\boldsymbol{y} = \boldsymbol{H}\, \boldsymbol{x} + \boldsymbol{v} \quad (8)$$

Where $\boldsymbol{H}$ is complex channel matrix with $N_R \times N_R$ dimension, its element h_{mn} denotes the channel fading coefficient between the n th transmit antenna and m th receive antenna. It is i.i.d. complex Gaussian random variable with zero mean and unit variance. $\boldsymbol{h_K}$ is the k th column of $\boldsymbol{H}$. Here we assume $\boldsymbol{H}$ is Rayleigh flat fading channel, and it is known to receiver.

Suppose the t th element of $\boldsymbol{x}$ is x_q . x_q is nonzero and it is the q th symbol of conventional constellation of M order modulation, then $\boldsymbol{x}$ can be denoted by $\mathbf{x_{tq}} = x\, \mathbf{e_t}$. Here $k\, \boldsymbol{e}$ is element vector of $N_T \times 1$ dimension [9], which denotes the k th element of the vector is 1, and the others are zero. So the received vector can be denoted by

$$\boldsymbol{y} = \boldsymbol{H}\, \boldsymbol{x} + \boldsymbol{v} = \boldsymbol{h_t}\, x_q + \boldsymbol{v} \quad (9)$$

Detection Algorithm for SM System

A. Existing algorithm and its constraint

Antenna index estimation based maximum ratio combining (MRC) is proposing in, which can be described as follows.

$$g_j = h_j^H y, (j = 1,2\ldots\ldots N_T) \quad (10)$$

$$\hat{t} = \arg\max\, ([|g_j|]_{j=1,2\ldots N_T}) \quad (11)$$

$$\hat{x_q} = Q\,(g_i) \quad (12)$$

where $[a_j]_{j=1,2,\ldots,K}$ denotes a vector composed of $a_1,a_2,\ldots,a_K$, and $Q(\cdot)$is constellation quantization function. Based on the estimated $\hat{t}$ and $\hat{x_q}$, the demodulated data can be obtained through demapping. We found however the above algorithm can only work efficiently under some conditions. Substitute (9) into (10) and neglect the effect of noise, we can get $g_j = h^H{}_j h_t x_q$, then substitute it into (11), we can see that if we want to get the correct antenna index (i.e. $|g_j|$ will be maximum when $j = t$), we require

$$|h^H{}_t h_t| = \|h_t\|^2 \geq |h^H{}_j h_t| \text{ , (j= 1,2,\ldots\ldots N_T)} \quad (13)$$

At the same time, the diagonal element of $\boldsymbol{H^H H}$ must be 1 if we want to get the correct demodulated symbols, that means

$$E[h_t^H h_j] = \delta_{i,j} \quad (14)$$

Where $\delta_{i,j}$ is Kronecker delta function. We call the channel meets the requirement of (13) and (14) constrained channel. If every column of an unconstrained channel matrix is normalized by its norm, then these conditions can be satisfied. So original SM detection algorithm can only be applied to constrained channel. Recently an optimal ML detection scheme for SM system is propose in [10], which search over all transmit antennas and all modulated symbols, then take the group with minimum Euclidean distance (MED) from the received vector as output. ML detection can be described as follow.

$$[\hat{t}, \hat{x_q}] = \arg\min \|y - Hx_{tq}\| = \arg\min \|y - x_q H e_t\| \quad (15)$$

Where $T1 \leq t \leq N_T$, $1 \leq q \leq M$, $x_q \in M$, M is the modulated symbols set. ML detection can be applied to unconstrained channel, but the complexity is very high, which can be seen from the complexity analysis later.

B. Detection algorithm based on normalized MRC

Based on the above analysis, every column of $\boldsymbol{H}$ should be normalize by its norm before estimation of antenna index, then MRC-based algorithm can be applied, we call it normalized MRC (NMRC) algorithm. For symbol demodulation, equation (9) is required to be left multiplied by $h^{\dagger}_t$ to get the estimation of x_q, where $(\cdot)^\dagger$ is Moore-Penrose inverse of a matrix. We know

$$h^\dagger_t = (h_t^H h_t)^{-1} h_t^H = h_t^H / \|h_t\|^2 \quad h^\dagger_t y = h_t^H y / \|h_t\|^2 \tag{16}$$

Therefore, the NMRC-based detection algorithm can described as Table 1.

C. Detection algorithm based on antenna index list

ML detection can be applied to unconstrained channel. However the complexity is very high because it requires searching over all transmit antennas and modulated symbols. Obviously reducing the candidates will decrease the complexity. Through further analysis, we found the accuracy of the first step (i.e. the estimation of antenna index) will greatly affect the overall performance of SM system during the detection process. This is because if the antenna index is wrong, we cannot recover the correct transmit information even exhausting search over all constellations is performed, and the BER performance will also be deteriorate rapidly. So the estimation of antenna index will dominate the overall performance. If we can increase the accuracy of the estimation of antenna index, the overall performance will be greatly improved.

Table 1 SM detection algorithm based on NMRC

Input: Channel Matrix $\boldsymbol{H} = [\boldsymbol{h}_1, \boldsymbol{h}_2, \cdots, \boldsymbol{h}_{N_T}]$,receive vector $\boldsymbol{y}$

Output: antenna index $\hat{i}$, demodulated symbol $\hat{x}_q$

1. Preprocess: $\bar{\boldsymbol{h}}_j = \boldsymbol{h}_j / \|\boldsymbol{h}_j\|$, $(j = 1, 2, \cdots, N_T)$
2. Estimation of antenna index (NMRC algorithm):
   2.1 $\bar{g}_j = \bar{\boldsymbol{h}}_j^H \boldsymbol{y}$, $(j = 1, 2, \cdots, N_T)$
   2.2 $\hat{i} = \arg\max_j \left(\left[|\bar{g}_j| \right]_{j=1,2,\cdots,N_T} \right)$
3. Symbol demodulation
   3.1 $g_{\hat{i}} = \boldsymbol{h}_{\hat{i}}^H \boldsymbol{y} / \|\boldsymbol{h}_{\hat{i}}\|^2 = \bar{g}_{\hat{i}} / \|\boldsymbol{h}_{\hat{i}}\|$
   3.2 $\hat{x}_q = \mathcal{Q}(g_{\hat{i}})$

Table 2 SM detection algorithm based on antenna index list

Input: Channel Matrix $\boldsymbol{H} = [\boldsymbol{h}_1, \boldsymbol{h}_2, \cdots, \boldsymbol{h}_{N_T}]$,receive vector $\boldsymbol{y}$

Output: antenna index $\hat{i}$,demodulated symbol $\hat{x}_q$

1. Preprocess: $\bar{\boldsymbol{h}}_j = \boldsymbol{h}_j / \|\boldsymbol{h}_j\|$, $(j = 1, 2, \cdots, N_T)$
2. List of antenna index (NMRC algorithm)
   2.1 $\bar{g}_j = \bar{\boldsymbol{h}}_j^H \boldsymbol{y}$, $(j = 1, 2, \cdots, N_T)$
   2.2 $\hat{i} = \arg\operatorname{maxv}_j \left(\left[|\bar{g}_j| \right]_{j=1,2,\cdots,N_T}, c \right)$
3. symbol demodulation
   3.1 $g_{\hat{i}_k} = \boldsymbol{h}_{\hat{i}_k}^H \boldsymbol{y} / \|\boldsymbol{h}_{\hat{i}_k}\|^2 = \bar{g}_{\hat{i}_k} / \|\boldsymbol{h}_{\hat{i}_k}\|$, $(k = 1, 2, \cdots, c)$
   3.2 $\hat{x}_{q,\hat{i}_k} = \mathcal{Q}(g_{\hat{i}_k})$, $(k = 1, 2, \cdots, c)$
4. MED search
   4.1 $\hat{k} = \arg\min_{k=1,2,\cdots,c} \|\boldsymbol{y} - \hat{x}_{q,\hat{i}_k} \boldsymbol{H} \boldsymbol{e}_{\hat{i}_k}\|$
   4.2 $\hat{i} = \hat{i}_{\hat{k}}$
   4.3 $\hat{x}_q = \hat{x}_{q,\hat{i}}$

Combining the complexity and the performance improvement, we proposed a new SM detection scheme base antenna index list (AI-List), which is shown in Table 2, where c is the candidates number of antenna index, and arg maxv($\boldsymbol{a}$,c) denotes the index of the maximum c elements in vector $\boldsymbol{a}$, it is also a vector. Obviously the choice of parameter c will affect the overall complexity and the performance.

D. Complexity analysis

Suppose the size of the constellation is M , and the complexity is evaluated by the numbers of float operation (flop). We know one complex multiplication needs 6 flops and one complex addition needs 2 flops. In the following, we take a whole detection process as example to evaluate the complexity of different algorithms. It's worth to note that the complexity of $(\cdot)^H$ and Q $(\cdot)$ can be neglected because they does not require additional operation. From the analysis of detailed operation process for every step [9], we can get that the preprocess needs $7N_T\ N_R$ flops, estimation of antenna index needs $N_T\ (8N_R - 2)$ flops, symbol demodulation only needs 2 flops because the data required for demodulation has already obtained in the above two steps and it only need a complex multiplication, a MED search needs $(12N_R - 1)$ flops. Therefore we can get the overall complexity of different algorithm, which is shown in Table 3. The complexity of VBLAST system with ZF ordered successive interference cancellation (OSIC) is also given in this table.

Table 3 Complexity of different detection algorithm

SM detection algorithm	Complexity (flops)
NMRC based SM detection	$15N_T N_R - 2N_T + 2$
AI-List SM detection	$15N_T N_R - 2N_T + c(12N_R + 1)$
ML detection	$MN_T(12N_R - 1)$
V-BLAST	$8N_T^4 + 16N_T^3 N_R + 8N_T^2 N_R + 18N_T N_R$

Result

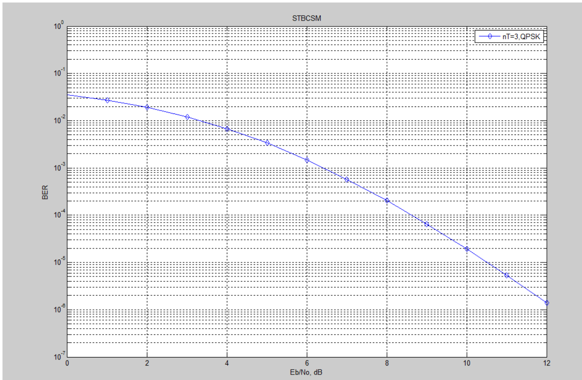

Fig.6 BER performance of QPSK modulation for 3 transmitting antennas

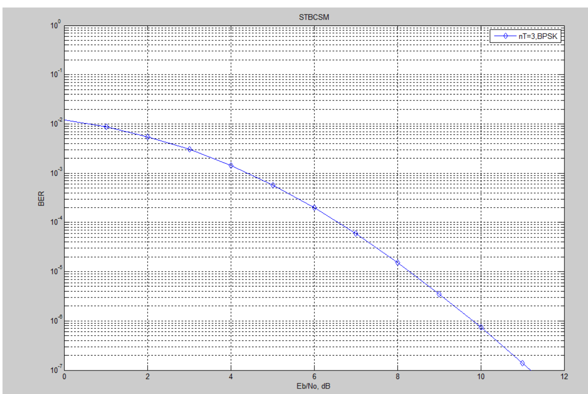

Fig.7 BER performance of BPSK modulation for 3 transmitting antennas

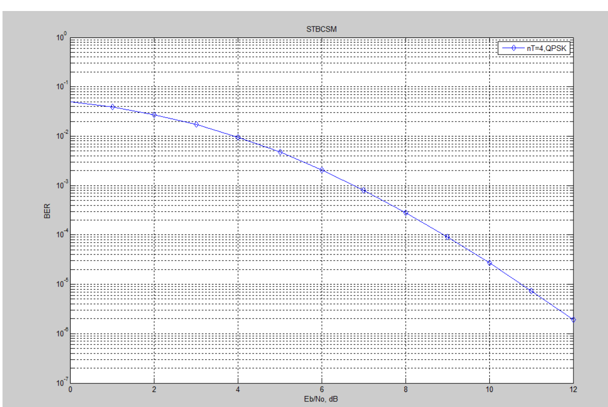

Fig.8 BER performance of QPSK modulation for 4 transmitting antennas

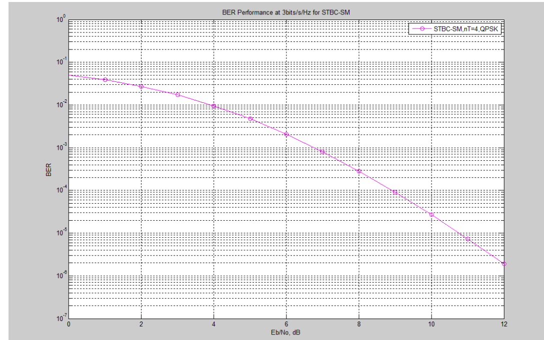

Fig.9 BER performance of STBC SM system under QPSK modulation for 4 transmitting antennas

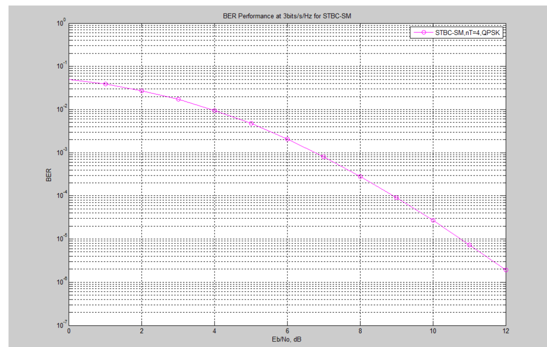

Fig.10 BER performance of STBC SM system under QPSK modulation for 4 transmitting antennas

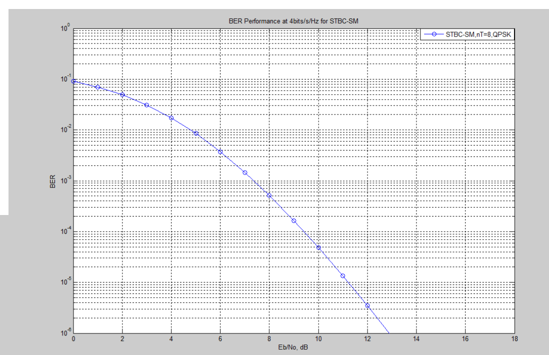

Fig.11 BER performance of STBC SM system under QPSK modulation for 8 transmitting antennas.

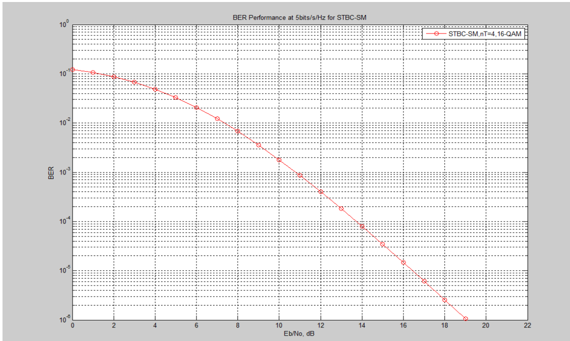

Fig.12 BER performance of STBC SM system under 16-QAM modulation for 4 transmitting antennas

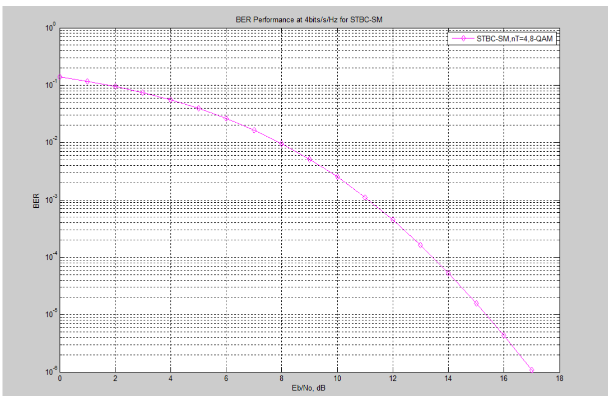

Fig.13 BER performance of STBC SM system under QAM modulation for 4 transmitting antennas

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