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### Abstract

This paper proposes a block spread orthogonal frequency division multiple access (BS-OFDMA) system with a combined space-time coded multiple-input multiple-out (STC-MIMO) scheme called STC-MIMO BS-OFDMA for transmission over frequency selective fading channels. In this system, a novel block spreading approach is firstly applied to effectively achieve precoding in the OFDMA system with lower complexity for improving the multipath diversity performance. The STC-MIMO is then incorporated to take advantage of the spatial diversity. The signal model and architecture of the proposed system are presented, and simulations are carried out to confirm the expected performance improvement.

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# Block Spread OFDMA System with Space-Time Coded MIMO over Frequency Selective Fading Channels

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**Abstract**—This paper proposes a block spread orthogonal frequency division multiple access (BS-OFDMA) system with a combined space-time coded multiple-input multiple-out (STC-MIMO) scheme called STC-MIMO BS-OFDMA for transmission over frequency selective fading channels. In this system, a novel block spreading approach is firstly applied to effectively achieve precoding in the OFDMA system with lower complexity for improving the multipath diversity performance. The STC-MIMO is then incorporated to take advantage of the spatial diversity. The signal model and architecture of the proposed system are presented, and simulations are carried out to confirm the expected performance improvement.

## I. INTRODUCTION

The orthogonal frequency division multiplexing (OFDM) scheme has received a large amount of attention in the literatures for achieving high data rate wireless transmission. OFDM has the capability to easily mitigate the intersymbol interference (ISI) and achieve bandwidth efficiency over frequency selective fading channels due to the orthogonality of subcarriers [1]. Therefore, OFDM has been widely used in recent digital communication systems such as wireless networks (WPANs/WLANs/WMANs) and digital audio/video broadcasting (DAB/DVB) [2]. Based on OFDM, orthogonal frequency division multiple access (OFDMA) has been introduced for multiuser applications.

Block spreading was first used with direct sequence and chip-interleaved block spread code division multiple access (DS-CDMA/CIBS-CDMA) to develop a multiuser interference (MUI) free receiver [3], [4]. The use of block spreading technology in OFDM systems was introduced by Bury et.al. [5] and further studied by McCloud [6]. The main idea of block spreading in OFDM is to linearly mix the transmitted data symbols across the subcarriers in order to achieve frequency diversity thereby minimizing the effect of frequency selective fading channels.

The use of multiple input multiple output (MIMO) in wireless communication systems has been widely considered due to its well known advantage of significant improvement to channel capacity and transmit diversity. Space-time coding (STC) is one of the MIMO techniques. It was originally designed for flat fading channels as it cannot tolerate the large delay spread that occurs in frequency selective fading channels [7]. According to [7], [8], however, the combination

of MIMO using STC with the OFDM technique works well because OFDM has the capability to transform frequency selective fading channels into multiple flat fading subchannels where space-time coding can be effectively applied, thereby improving system performance even over channels with large delay spreads.

In this paper, we extend the idea of block spread OFDM (BOFDM) and STC-MIMO OFDM [8]–[10] to a combined block spread STC-MIMO OFDMA system for multiuser application. According to [11], at the transmitter, the combination of block spreading with OFDM is usually implemented by a precoding process of assigning a spreading matrix followed by an inverse fast Fourier transform (IFFT). In our system, however, either precoding process for block spreading or IFFT modulation for OFDMA is not required as we effectively combine block spread with OFDMA using a complex spreading sequence. Then, STC-MIMO using the Alamouti code [12] is further applied to gain an additional diversity. A relevant receiver architecture is developed for block despreading, MIMO decoding and channel equalization. Finally, performance evaluation and comparison are conducted to demonstrate the anticipated improvement.

The novel contributions of this paper include 1) the application of a new approach to effectively combine block spreading technique with OFDMA modulation to obtain improved performance and greatly reduce system complexity at the same time; 2) the implementation of STC-MIMO using Alamouti code is further performed in the frequency domain to gain multipath diversity; 3) the minimum mean square error (MMSE) equalization is designed as a decoding method for the proposed block spread STC-MIMO OFDMA systems.

The paper is organized as follows. In Section II, the block spread STC-MIMO OFDMA system model is presented. Section III describes the receiver architecture and detailed decoding algorithms based on the combined MIMO decoding and MMSE frequency domain equalization. Simulation results are given in Section IV. Finally conclusions are drawn in Section V.

## II. STC-MIMO BS-OFDMA SIGNAL MODEL

The structure of the block spread STC-MIMO OFDMA transmitter is shown in Fig. 1. we first describe the method

to effectively combine block spread with OFDMA without using any spreading matrices or an IFFT processor. The output signals from BSOFDMA module are then encoded by the STC-MIMO encoder to implement the Alamouti code in the frequency domain.

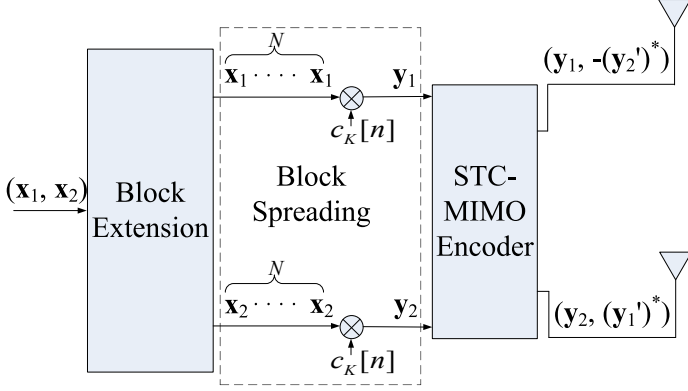


Fig. 1. Block spread STC-MIMO OFDMA transmitter model.

As shown in Fig. 1, we group two vectors  $\mathbf{x}_1$  and  $\mathbf{x}_2$ , where  $\mathbf{x}_1 = (x_1[0], \dots, x_1[M-1])$  and  $\mathbf{x}_2 = (x_2[0], \dots, x_2[M-1])$  are two consecutive block modulated symbol vectors after Quadrature Phase Shift Keying (QPSK) modulation. The length of each symbol vector is  $M$ , which is an integer power of 2. The symbol vector  $\mathbf{x}_1$  and  $\mathbf{x}_2$  are first sent to a block extension module, where each vector is extended to  $MN$  length by simply duplicating itself for  $N$  times. Then a complex exponential sequence  $c_K[n]$  is assigned to those extended vectors to implement block spreading. It is expressed as

$$c_K[n] = \exp(j \frac{2\pi K n}{N}), \quad n = 0, 1, \dots, N-1, K = 0, 1, \dots, N-1, \quad (1)$$

where  $K$  is the user index to identify a specific user and  $N$  denotes the number of users in the system. In addition to block spreading,  $c_K[n]$  is also used to generate OFDMA signals as it constitutes a set of orthogonal functions with each user differentiated by a distinct frequency. Therefore, the block spreading technique and OFDMA modulation are effectively combined in our system without any precoding process and IFFT implementation, and, as a result, the system computational complexity is greatly reduced. The process of block spreading and OFDMA modulation can be illustrated in Fig. 2. The elements of the output symbol vector  $\mathbf{y}_1 = (y_1[0], \dots, y_1[MN-1])$  and  $\mathbf{y}_2 = (y_2[0], \dots, y_2[MN-1])$  are expressed as

$$\begin{aligned} y_1[i] &= x_1[m]c_K[n], \\ y_2[i] &= x_2[m]c_K[n], \\ i &= nM + m, \\ m &= 0, 1, \dots, M-1, n = 0, 1, \dots, N-1. \end{aligned} \quad (2)$$

The main advantage of the block spread OFDMA is its improved frequency diversity performance for combating frequency selective fading channels. This can be easily analyzed

by transforming the signal model to frequency domain. After performing the  $MN$ -point DFT of  $y_t[i]$ ,  $t = 1$  or  $2$ , we obtain

$$\begin{aligned} Y_t[k] &= \sum_{i=0}^{MN-1} y_t[i] e^{-j \frac{2\pi}{MN} ki} \\ &\stackrel{i=nM+m}{=} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} y_t[nM+m] e^{-j \frac{2\pi}{N} kn} e^{-j \frac{2\pi}{MN} km} \\ &= \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} x_t[m] c_K[n] e^{-j \frac{2\pi}{N} kn} e^{-j \frac{2\pi}{MN} km} \\ &= \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} x_t[m] e^{j \frac{2\pi K}{N} n} e^{-j \frac{2\pi}{N} kn} e^{-j \frac{2\pi}{MN} km} \\ &= \sum_{m=0}^{M-1} x_t[m] e^{-j \frac{2\pi}{MN} km} \sum_{n=0}^{N-1} e^{-j \frac{2\pi}{N} (k-K)n} \\ &= \begin{cases} X_{K,t}[l], & k = lN + K, l = 0, 1, \dots, M-1 \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (3)$$

where

$$X_{K,t}[l] = N \sum_{m=0}^{M-1} x_t[m] e^{-j \frac{2\pi}{MN} (lN+K)m}, \quad l = 0, 1, \dots, M-1. \quad (4)$$

Eq. 3 and Eq. 4 imply that the  $M$  data symbols of the  $K$ th user are first mixed via a phase rotation matrix  $\mathbf{W}_M = (e^{-j \frac{2\pi}{MN} (lN+K)m})$  to obtain precoded symbols  $X_{K,t}[l]$ ,  $l = 0, 1, \dots, M-1$ , and then spread across  $M$  equally spaced subcarriers  $k = lN + K$ . It is illustrated in Fig. 3, where the number of users is  $N = 4$  and each user carries  $M = 8$  data symbols. Note that each subcarrier of a specific user in Fig. 3 no longer takes a single data symbol but a set of all data symbols combined together. Therefore, the frequency diversity is achieved, and an improved performance over frequency selective fading channels is thus expected.

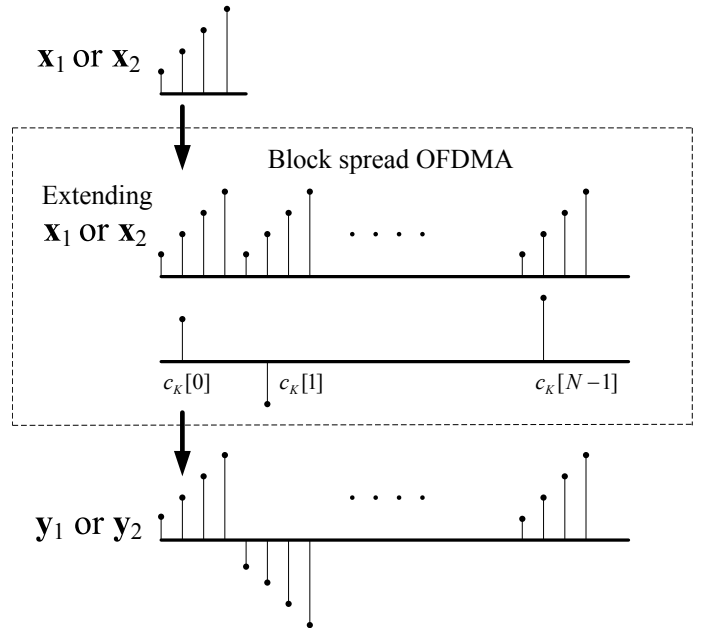


Fig. 2. Process of block spreading and OFDMA modulation.

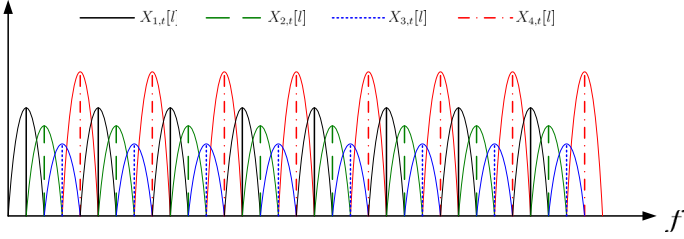


Fig. 3. Block spread OFDMA signal characteristics in frequency domain.

We consider two transmit antennas for the STC-MIMO design following the block spread OFDMA module. We propose a new approach using the Alamouti code in the frequency domain to implement the space-time encoding, which is different from the previous STC-MIMO schemes that the Alamouti code is applied to the time domain [13], [14]. However, based on the conjugation property of Fourier transform relations between time domain and frequency domain, the STC-MIMO encoding is actually performed in the time domain so that the block spreading can be easily incorporated. This process is shown in Fig. 4. In order to obtain a conjugation of the signal in the frequency domain, we maintain the first symbol and reverse the remaining symbols of the input vectors  $\mathbf{y}_1$  and  $\mathbf{y}_2$  respectively to generate  $\hat{\mathbf{y}}_1$  and  $\hat{\mathbf{y}}_2$  in the time domain. Theoretically, this is equivalent to periodically extending the  $\mathbf{y}_1$  and  $\mathbf{y}_2$ , then reversing all symbols and taking one period. At a given time slot,  $\mathbf{y}_1$  is transmitted from transmitter one and  $\mathbf{y}_2$  is transmitted from transmitter two. During the next time slot,  $-(\hat{\mathbf{y}}_2)^*$  and  $(\hat{\mathbf{y}}_1)^*$  are transmitted from transmitter one and two, respectively, where  $*$  denotes the complex conjugation. As a result, the Alamouti code can be accordingly realized in the frequency domain.

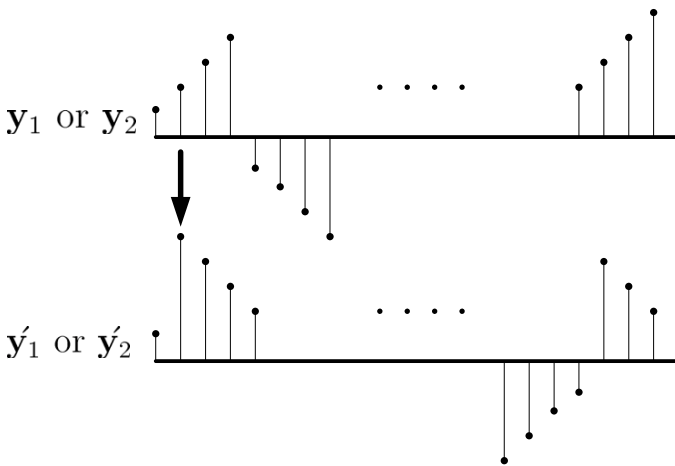


Fig. 4. Process in the time domain to implement STC-MIMO.

To avoid the inter symbol interference (ISI) due to the effect of frequency selective channels, a cyclic prefix (CP) of a sufficient length (longer than the maximum path delay) is appended to each symbol vector before transmission.

### III. MMSE DECODING ALGORITHM

The received signals are first demodulated at the STC-MIMO decoder to yield baseband signals. To simplify the system, we only consider the receiver equipped with one antenna. The receiver is shown in Fig. 5, where  $\mathbf{W}_M^{-1}$  is the inverse matrix of  $\mathbf{W}_M$  defined in the previous section.

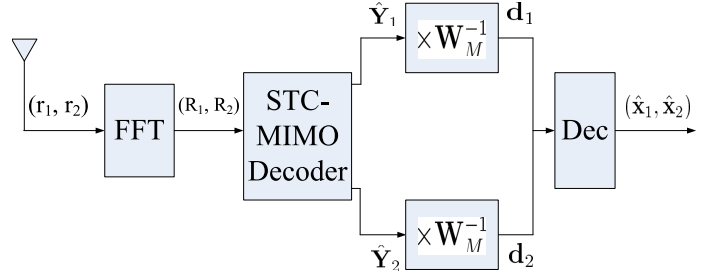


Fig. 5. Block spread STC-MIMO OFDMA receiver model.

The decoding process can be performed in the frequency domain. Let  $H_1[k]$  and  $H_2[k]$  be the channel frequency responses for the  $k$ -th subcarrier corresponding to two transmit and one receive antennas. We assume that the channel responses are constant during periods of two consecutive block data vectors and known to the receiver. After removing the cyclic prefix, the  $MN$ -point fast Fourier transform (FFT) and  $N$  factor down-sampling are implemented to generate frequency domain signals. Thus, the received signals in the frequency domain can be expressed by  $R_1[k]$  and  $R_2[k]$ ,  $k = 0, 1, \dots, M-1$ , as

$$R_1[k] = Y_1[k]H_1[k] + Y_2[k]H_2[k] + V_1[k], \quad (5)$$

$$R_2[k] = -Y_2^*[k]H_1[k] + Y_1^*[k]H_2[k] + V_2[k], \quad (6)$$

where  $V_1[k]$  and  $V_2[k]$  are noise samples for  $k$ -th subcarrier on each channel that can be modeled as complex Gaussian random variables with zero mean and power  $N_0/2$  per dimension. To group the received symbols to be vector expression, the above equations can be equivalently expressed as follows,

$$\mathbf{R}_1 = \mathbf{Y}_1\mathbf{H}_1 + \mathbf{Y}_2\mathbf{H}_2 + \mathbf{V}_1, \quad (7)$$

$$\mathbf{R}_2 = -\mathbf{Y}_2^*\mathbf{H}_1 + \mathbf{Y}_1^*\mathbf{H}_2 + \mathbf{V}_2, \quad (8)$$

where we denote

$$\begin{aligned} \mathbf{R}_1 &= (R_1[0], R_1[1], \dots, R_1[M-1]), \\ \mathbf{R}_2 &= (R_2[0], R_2[1], \dots, R_2[M-1]), \\ \mathbf{Y}_1 &= (Y_1[0], Y_1[1], \dots, Y_1[M-1]), \\ \mathbf{Y}_2 &= (Y_2[0], Y_2[1], \dots, Y_2[M-1]), \\ \mathbf{H}_1 &= \text{diag}(H_1[0], H_1[1], \dots, H_1[M-1]), \\ \mathbf{H}_2 &= \text{diag}(H_2[0], H_2[1], \dots, H_2[M-1]), \\ \mathbf{V}_1 &= (V_1[0], V_1[1], \dots, V_1[M-1]), \\ \mathbf{V}_2 &= (V_2[0], V_2[1], \dots, V_2[M-1]). \end{aligned} \quad (9)$$

For simplicity of expression, we define  $\mathbf{R} = (\mathbf{R}_1, \mathbf{R}_2^*)$ ,  $\mathbf{Y} = (\mathbf{Y}_1, \mathbf{Y}_2)$ ,  $\mathbf{H} = \begin{pmatrix} \mathbf{H}_1 & \mathbf{H}_2^* \\ \mathbf{H}_2 & -\mathbf{H}_1^* \end{pmatrix}$  and  $\mathbf{V} = (\mathbf{V}_1, \mathbf{V}_2^*)$ . Thus, Eq. 7 and Eq. 8 can be rewritten in a matrix form as

$$\mathbf{R} = \mathbf{Y}\mathbf{H} + \mathbf{V}. \quad (10)$$

The MMSE equalization is preferable for the frequency domain equalization design as it offers a trade-off between the high complexity of maximum likelihood (ML) detection and the poor performance of zero-forcing (ZF) equalization. Let  $\mathbf{C}$  denote the equalizer coefficient and  $\hat{\mathbf{Y}}$  represent the MIMO decoding vector, where  $\hat{\mathbf{Y}} = (\hat{\mathbf{Y}}_1, \hat{\mathbf{Y}}_2) = \mathbf{RC}$ . When the MMSE criterion is used, i.e.,  $\varepsilon^2 = E \{(\hat{\mathbf{Y}} - \mathbf{Y})^\dagger (\hat{\mathbf{Y}} - \mathbf{Y})\}$  is minimized, we have

$$\mathbf{C} = \mathbf{H}^\dagger \left( \mathbf{H}\mathbf{H}^\dagger + \frac{1}{\gamma_{in}} \mathbf{I} \right)^{-1}, \quad (11)$$

where  $(\cdot)^\dagger$  denotes matrix transposition and complex-conjugation operation,  $\mathbf{I}$  is the identity matrix with the same size of  $\mathbf{H}$ , and  $\gamma_{in}$  is the input SNR before equalization. Then  $\hat{\mathbf{Y}}$  is sent to the following block despreading module to generate the decision variable vector  $\mathbf{d}$ .

The OFDMA block decoding algorithm can be simply addressed by performing a despreading matrix  $\mathbf{W}_M^{-1}$ , which is easily obtained from  $\mathbf{W}_M$  as

$$\begin{aligned} \mathbf{W}_M^{-1} &= \left( \frac{1}{N} e^{j \frac{2\pi}{MN} (K+iN) \times m} \right), \\ i &= 0, 1, \dots, M-1, \\ m &= 0, 1, \dots, M-1. \end{aligned} \quad (12)$$

As a result, the decision variable  $\mathbf{d} = (\mathbf{d}_1, \mathbf{d}_2)$  can be obtained by

$$\begin{aligned} \mathbf{d}_1 &= \hat{\mathbf{Y}}_1 \mathbf{W}_M^{-1}, \\ \mathbf{d}_2 &= \hat{\mathbf{Y}}_2 \mathbf{W}_M^{-1}, \end{aligned} \quad (13)$$

and the transmitted data symbol  $\hat{\mathbf{x}} = (\hat{x}_1, \hat{x}_2)$  can be retrieved after hard decision on the decision variable  $\mathbf{d} = (\mathbf{d}_1, \mathbf{d}_2)$ .

#### IV. SIMULATION RESULTS

In this section, we provide simulation results for the proposed block spread OFDMA system with STC-MIMO using the Alamouti code for two transmit antennas and one receive antenna. Simulations are carried out based on the theoretical analysis mentioned in the previous sections. The parameters used for the simulations are given in Table I. We compare the bit error performance of the proposed system with that of conventional OFDMA system (without STC-MIMO or block spreading), STC-MIMO OFDMA system (without block spread) and block spread OFDMA system (without STC-MIMO). In a multiuser environment, we only consider the simulation on a specific user according to its user index of  $K$ , which can be any value from 0 to  $N-1$  ( $N$  is the total number of users in the system). While conducting MIMO simulations, we assume that the transmit antennas are uncorrelated so that the fading effects on those antennas can be considered to be independent. We also normalize the power of signals transmitted from each antenna to be half in order to maintain the total transmitted power equal to a single antenna system. Regarding the simulation of frequency selective multipath fading channels, we use the tapped delay line model and assume a multipath diversity of order  $L_P$ , and we also assume all channel coefficients are independent and

TABLE I  
PARAMETERS FOR SIMULATIONS

Parameter	Value
Number of users $N$	8
Index of a specific user $K$	3
Size of block unit $M$	16 or 32
Cyclic prefix length $L$	16
Number of multipaths $L_P$	8
Maximum Doppler frequency	50Hz
Modulation	QPSK
Number of simulation runs	10000

presented as complex Gaussian random variables with zero-mean and variance  $\frac{1}{L_P}$ .

Fig. 6 shows the bit error rate (BER) performance comparison of the proposed block spread STC-MIMO OFDMA system with the conventional OFDMA system and the OFDMA system with either block spreading or STC-MIMO. In this case, the size of block spreading unit that we use in our simulation is  $M = 16$ . We can see from the figure that the use of block spreading provides improved BER performance for the OFDMA system by achieving 7dB SNR gain over the conventional OFDMA system at  $\text{BER} = 10^{-4}$ . In addition, the block spread OFDMA system works better than the STC-MIMO OFDMA system when SNR is small ( $\text{SNR} < 20\text{dB}$ ). For example, the former can achieve 3dB SNR gain over the latter at  $\text{BER} = 10^{-3}$ . However, those two performance curves come close at high SNRs. Therefore, we can estimate that the STC-MIMO OFDMA system may provide better performance than the block spread OFDMA system when SNR goes high. The proposed STC-MIMO BS-OFDMA system performs the best among the considered systems in terms of an 8dB SNR gain over the block spread OFDMA system and the STC-MIMO OFDMA system, respectively, at  $\text{BER} = 10^{-5}$ .

In Fig. 7, we increase the block spreading size to  $M = 32$ . Similarly, the proposed STC-MIMO BS-OFDMA system provides the best BER performance. It provides an 8dB SNR gain over the STC-MIMO OFDMA system and a 13dB SNR gain over the OFDMA system, respectively, at  $\text{BER} = 10^{-3}$ . Moreover, it provides a 9dB SNR gain over the BS-OFDMA system at  $\text{BER} = 10^{-6}$ . Comparing Fig. 7 with Fig. 6, we notice that performance can be further improved by increasing the block spreading size. For example, to achieve the same  $\text{BER} = 10^{-5}$ , 9dB SNR is required for STC-MIMO BS-OFDMA system with  $M = 16$  while 7dB SNR is required for that with  $M = 32$ .

In Fig. 8, we simulate the block spread STC-MIMO OFDMA system and the block spread OFDMA system with MMSE and ZF equalizations, respectively. We see that for both systems performance is improved significantly when MMSE equalization is used.

#### V. CONCLUSION

In this paper, a block spread OFDMA system combined with a STC-MIMO scheme is proposed for performance improvement over frequency selective fading channels. Compared with a conventional OFDMA system, the block spreading

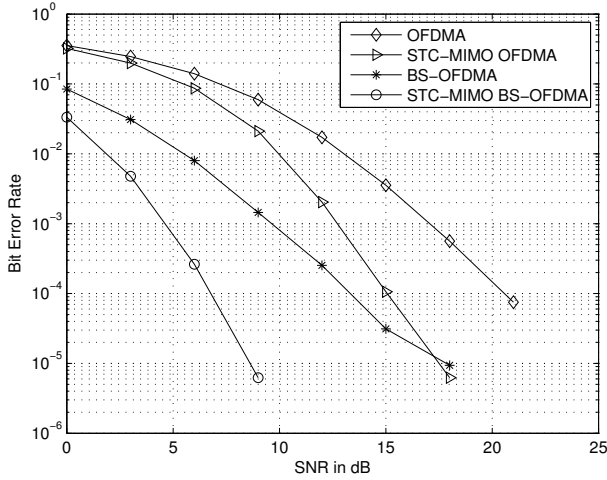


Fig. 6. Performance comparison of block spread STC-MIMO OFDMA system with other schemes when  $M = 16$ .

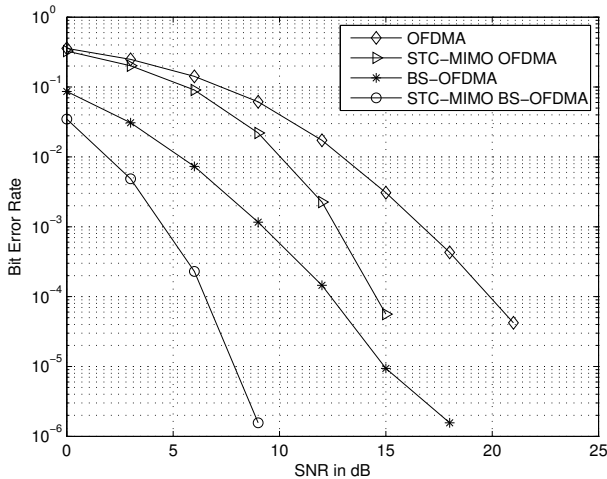


Fig. 7. Performance comparison of block spread STC-MIMO OFDMA system with other schemes when  $M = 32$ .

technique is applied to mitigate the frequency selective fading by providing a frequency diversity, thereby improving the system performance. According to our novel approach, the block spread and OFDMA scheme can be easily combined without any explicit precoding method thus greatly reducing the system complexity. STC-MIMO is further used to obtain a spatial advantage at the cost of a slightly more complicated system structure. Simulations show that the proposed block spread STC-MIMO OFDMA system can provide much better bit error performance compared with other schemes.

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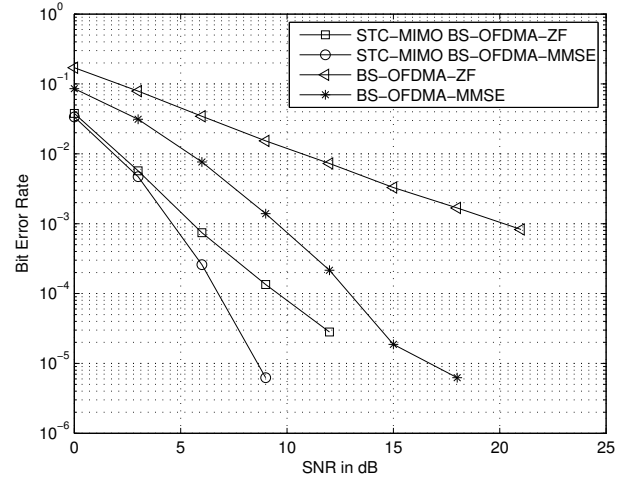


Fig. 8. Performance comparison of MMSE and ZF equalizations.

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