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Research Article

SINR Analysis and Performance Evaluation of Space-Time-Frequency spread MIMO-OFDM-CDMA system using MMSE Receiver

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Abstract

MIMO-OFDM-CDMA system has been identified as a key technology to support high data rates in current and future wireless systems. MMSE receiver plays an important role in the performance evaluation of MIMO-OFDM-CDMA system. In this paper, we propose a detailed Signal-to-Interference Noise Ratio (SINR) analysis for space-time-frequency spread MIMO-OFDM-CDMA system using MMSE receiver. The accurate expressions for SINR have been derived for MMSE receiver. Further, the performance of such 4x4 MIMO system has also been evaluated and compared with zero forcing (ZF) receiver through simulation. The simulation results of the MIMO-OFDM-CDMA system are in line with the results obtained through mathematical analysis and MMSE receiver performs better than ZF receiver.

Keywords: *Code Division Multiple Access (CDMA), Minimum Mean Square Error (MMSE) Receiver, Multiple Access Interference (MAI), Multiple-Input Multiple-Output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), Space-Time-Frequency (STF) Spreading, Signal to Interference Noise Ratio (SINR), Zero Forcing (ZF) Receiver.*

Introduction

The demand for wireless communication services have grown rapidly in the past. This is expected to continue in the future as well. To satisfy the increasing demands for wireless communication services, advanced features are introduced in the present cellular systems. Other than that, the future generation cellular system is expected to solve the problems that exist in the present system and it also replaces the entire cellular network with a single worldwide cellular network with IP interoperability for seamless mobile internet access, high speed, global roaming, high capacity and low cost per bit (M. Jamil, *et al,* 2008; D. Mahjabeen, *et al,* 2010). MIMO-OFDM-CDMA for the next generation wireless mobile combines the advantages of the three robust techniques namely OFDM, CDMA and MIMO. MIMO-OFDM-CDMA system has been identified as a key technology to support high data rates in current and future wireless systems (U. Urosevic, *et al,* 2011).

Orthogonal frequency division multiplexing (OFDM) technique has attracted a lot of attention in the standardization of 4G broadband wireless systems. The basic principle of OFDM is to divide a high-rate data stream into numbers of low-rate streams, which are transmitted simultaneously over a number of subcarriers or subchannels, while making all the subcarriers orthogonal to one another. However, it suffers from many difficulties such as large peak-to-average-power ratio (PAPR) and adding a guard period lowers the symbol rate and hence lowers the overall spectral efficiency of the system etc. (M. Jiang, *et al,* 2007). In order to combat these difficulties, OFDM is made to combine with CDMA (Code Division Multiple Access) and the combination is known as multicarrier-CDMA, MC-CDMA and OFDM-CDMA system. Hence OFDM-CDMA system has emerged as a promising air-interface for future high data rate wireless communication to achieve high capacity and high robustness without excessive complexity (F. Adachi, *et al,* 2005).

In order to meet the requirements of the broadband wireless access, OFDM-CDMA system is further combined with MIMO technique i.e. the use of multiple antennas at transmitter/receiver. The main idea behind using this system is to utilize the spectrum efficiently with less complexity, maximum diversity and high throughput (H. Yang, *et al,* 2005).

In this article, the STF spread MIMO-OFDM-CDMA system proposed in (H. Dahman, *et al,* 2011) has been analyzed by considering minimum mean square error receiver (MMSE) receiver in contrast to ZF receiver in (H. Dahman, *et al,* 2011). MMSE receiver offers many advantages over ZF receiver. It suppresses both interference and noise components, has better probability of error performance and has simple

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structure. The accurate expressions for SINR have been derived here for MMSE receiver. Further, the probability of error results of STF spread MIMO-OFDM-CDMA system using MMSE receiver has been presented in detail and compared with that of ZF receiver.

The rest of the paper is organized as follows. Section II presents the introduction of linear receivers. Section III depicts a MIMO-OFDM-CDMA system model. Section IV describes the detailed mathematical analysis of MMSE receiver in MIMO-OFDM-CDMA system. The performance evaluation including system parameters and simulation results are presented in section V followed by a conclusion in section VI.

Linear Receivers

In current wireless communication system, a very high speed transmission system is required for various applications. For such a system, a receiver with less complexity becomes more and more important. Thus, linear receivers such as Zero-Forcing (ZF) receiver (or detector) or Minimum Mean–Square Error (MMSE) receiver (or detector) have attracted more and more attention (S. Moshavi, *et al,* 2002).

ZF Receiver

ZF Receiver is a linear receiver and it is also known as decorrelator or interference nulling receiver. It behaves like a linear filter and separates the data streams and thereafter decodes each stream. We assume channel matrix H is invertible and estimate the reconstructed data signal as in (M. Dakhli, *et al,* 2011).

$$\hat{x} = (H^H H)^{-1} H y \qquad (1)$$

ZF is based upon nulling all other users signal by using pseudo-inverse$(H^H H)^{-1}$, in order to make a decision about the desired user's signal. Since an inverse of H can only exist if the columns of H are independent and where subscript H denotes the complex conjugate transpose and y is the received signal. The ZF receiver perfectly separates the co-channel's signals but at the cost of noise enhancement at the receiver output. The advantages of ZF receiver includes lower cost, less computational complexity, simple design, removes ISI completely and its relatively good performance at high SNR region.

MMSE Receiver

The minimum mean-squared error (MMSE) receiver is a linear receiver which takes into account the background noise and utilizes the knowledge of the received signals power. In this, linear mapping is done which minimizes the mean-squared error between the actual data and the soft output of conventional receiver. The reconstructed data signal by using MMSE receiver is given as in (V. Jagan, *et al,* 2010).

$$\hat{x} = (H^H H + \sigma^2 \mathrm{I})^{-1} H y \qquad (2)$$

Where, H is the channel matrix, I is the Identity matrix, σ^2 is the noise variance and superscript H denotes the complex conjugate transpose.

The MMSE receiver considers the background noise, so it generally provides better probability of error performance. As background noise goes to zero, the MMSE receiver converges to ZF receiver. The MMSE receiver can also minimize the overall error caused by noise and mutual interference between the co-channel signals, but at the cost of separation quality of the signals. The main benefit of MMSE receiver is that it does not allow noise enhancement as compared to ZF receiver but some residual ISI will be observed at the output (A. Khare, *et al,* 2011; S. Singh, *et al,* 2011). However, this residual ISI at the output of the receiver does not lead to significant performance degradation.

System Model

In this section, the detailed model of STF spread MIMO-OFDM-CDMA system as proposed in (H. Dahman, *et al,* 2011) is being discussed by using MMSE receiver instead of ZF receiver. The said system is being presented in figure 1.

MIMO-OFDM-CDMA Transmitter

Figure 1(a) shows the system architecture of MIMO-OFDM-CDMA system withN_t transmit andN_r receive antennas and where$(N_r \geq N_t)$ for the proper detection of the signal and $K_n$stands for K-th subcarrier at time n (n=1, 2, ...,N_C). At the transmitter, multiuser multiplexing is employed, where all the users are added together and then it is serial to parallel converted, after that each bit stream for each antenna are coded separately and then mapped to their corresponding symbols. Next all the symbols are grouped into N_f symbols in IFFT where frequency domain symbols are converted into time domain symbols. Then it is spread with a size N_C using joint STF-domain spreading by Walsh Hadamard codes where $N_f > N_C$ to ensure orthogonality between users (N. Sinha, *et al,* 2010). Now the detail description of joint STF spreading is discussed below as shown in figure 1(b), where the signal is first spread in space, followed by time spreading and lastly by time-frequency mapping as in (H. Dahman, *et al,* 2011).

1) Space Spreading

Firstly the signal is spread in space domain for the transmission by using Walsh Hadamard orthogonal codes or columns of FFT matrix. Let x_k be the transmitted symbol from user k, then after spreading,

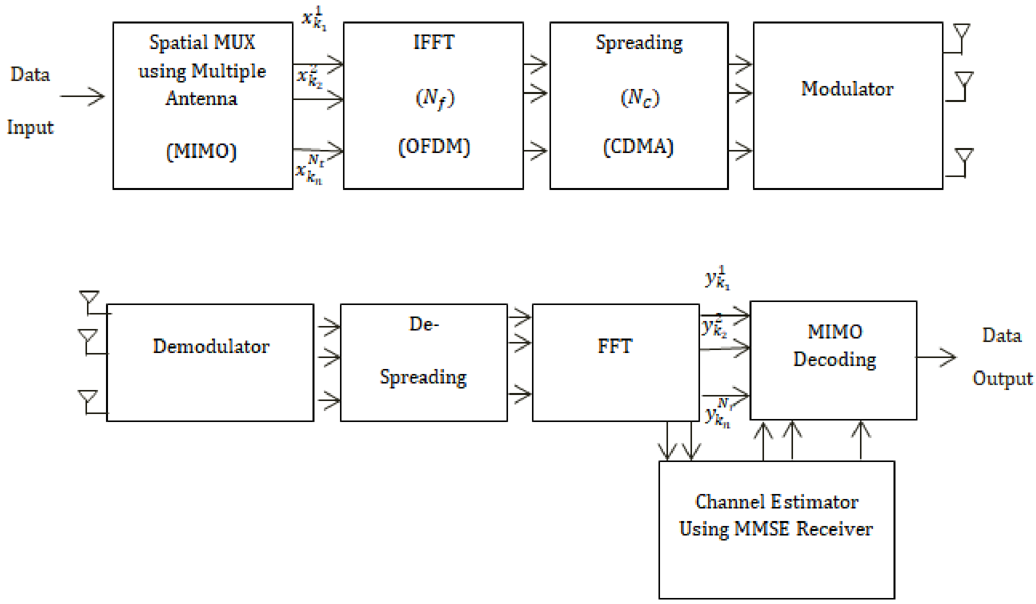
$$x'_k = s_k x_k$$

$$= [x'_{k,1}, x'_{k,2}, \ldots . x'_{k,N_t}]; \qquad k = 1,2, \ldots \ldots M \text{ ``} \qquad (3)$$

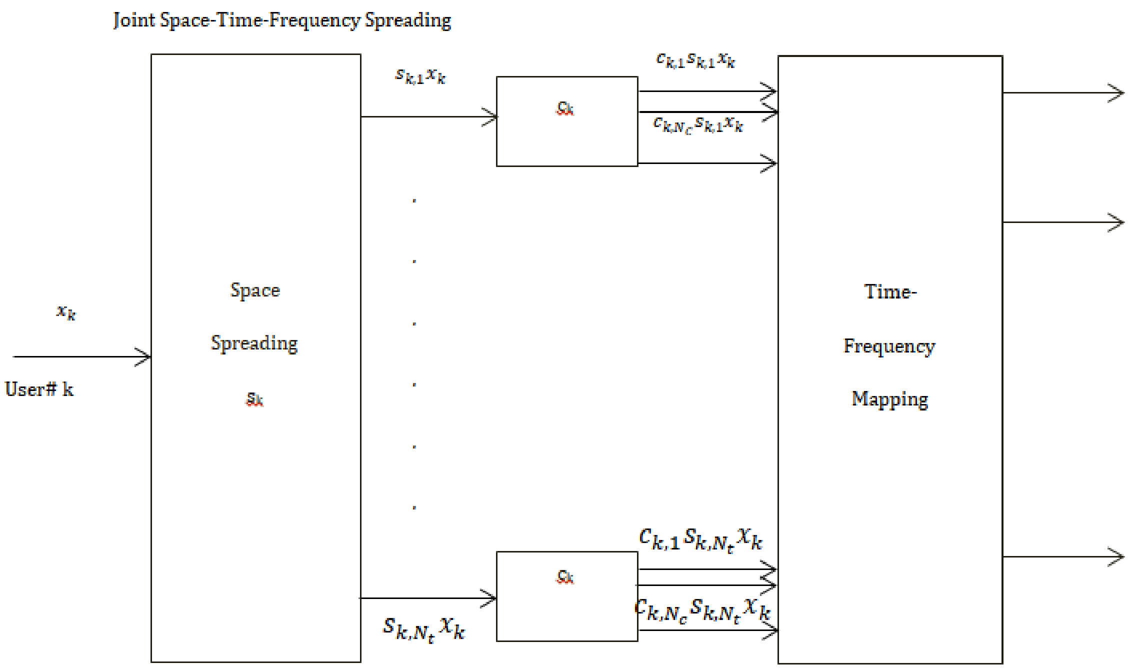
Where x'_k denotes the spread signal from user k and M is the number of users in the system and $s_k = [s_{k,1}, s_{k,2}, \ldots \ldots s_{k,N_t}]^T$ is the orthogonal code with size N_t.

2) *Time Spreading*

After the space spreading, time spreading of the transmitted signal x'_k is done by using c_k orthogonal code for user k with size N_C.



(a) MIMO-OFDM-CDMA system



(b) Joint STF Spreading block diagram

Fig. 1: Block diagram of STF spread MIMO-OFDM-CDMA System

Let x_k'' be the spread signal in time domain,

$$x_{k,i}'' = c_k x_{k,i}'$$

$$= \left[x_{k,i,1}'' , x_{k,i,2}'' , \ldots\ldots x_{k,i,N_C}''\right]^T; \qquad i = 1,2,..N_t \qquad (4)$$

Where $x_{k,i,n}''$ is the transmitted signal for user k from antenna i at time n (n=1, 2, ...,N_C) and N_C is the length of spreading code.

3) Time-Frequency Mapping

Before IFFT operation, time-frequency mapping is performed at the resultant of space-time spreading i.e. $x_{k,i}''$. Here all the users will use the same mapping method at each antenna. Let's consider the mapping for $x_{k,1}''$ and assume $x_{k,1,1}''$ occupies OFDM symbol 1 at subcarrier K_1, $x_{k,1,2}''$ occupies OFDM symbol 2 at subcarrier K_2 and $x_{k,1,N_C}''$ occupies OFDM symbol N_C at subcarrier K_{N_C}.

The next transmitted signal $x_{k,1,1}''$ occupies OFDM symbol 1 at subcarrier $K_1 + 1$, $x_{k,1,2}''$ occupies OFDM symbol 2 at subcarrier $K_2 + 1$. Subsequent symbols will be spread in the same manner as symbols 1 and 2. After all the spreading, the output signals are modulated using QPSK modulation and then with the help of N_t transmit antennas, it is transmitted into channel. The channel is assumed to be Rayleigh fading i.e., the elements of the matrices $H(l)(l = 0, 1, \ldots\ldots L' - 1$ are independent circularly symmetric complex Gaussian random variable with zero mean and variance σ_l^2, where $H(l)$ is lth tap and L' is the channel length (H. Dahman, *et al,* 2011).

MIMO-OFDM-CDMA Receiver

At the receiver, just the reverse operation of transmitter is performed. Firstly, the signal is received through N_r receive antennas as shown in equation (5) and then it is demodulated. Thereafter, despreading is being carried out followed by an FFT operation of size N_f. After going through MIMO decoding block, the reconstructed data is obtained with the help of channel estimator using MMSE receiver as shown in equation (10).

Detailed mathematical analysis of MIMO-OFDM-CDMA system using MMSE receiver

In this section, the accurate SINR expressions for STF spread MIMO-OFDM-CDMA system using MMSE receiver have been derived. With the help of Walsh-Hadamard codes, each user is assigned with different space spreading code s_k and time spreading code c_k. Then the received signal will be as in (*H. Dahman, et al,* 2011)

$$y_{K_n} = \sum_{k=1}^{M} \left(H_{K_n} c_{k,n} s_k\right) x_k + n_{K_n}, \; 1 \le K_n \le N_f \qquad (5)$$

Where K_n stands for K-th subcarrier at time n (n=1, 2, ...,N_C), k stands for user index, H_{K_n} is the impulse response of the channel K-th subcarrier at time n and N_f is the size of FFT matrix.

Stacking the entire received signal in a column, we get

$$\underbrace{\begin{bmatrix} y_{K_1} \\ y_{K_2} \\ \vdots \\ y_{K_{N_c}} \end{bmatrix}} = \widetilde{H}\tilde{s}_1 x_1 + \widetilde{H}\tilde{s}_2 x_2 + \cdots + \widetilde{H}\tilde{s}_M x_M + n \qquad (6)$$

$$= \underbrace{\left[\widehat{H}_1 \widehat{H}_2 \quad \ldots \quad \widehat{H}_M\right]}_{\mathrm{G}} x + n \qquad (7)$$

Where $\widetilde{H}$ is the modified channel matrix for N_C subcarriers, $\widehat{H}_k$ is the effective channel ($N_C N_r \times 1$) for user k and $\tilde{s}_k = c_k \otimes s_k$ is the combined spatial-time spreading code and $\otimes$ is the Kronecker product matrix where,

$$\tilde{s}_k = \begin{bmatrix} c_{k,1} \\ c_{k,2} \\ \vdots \\ c_{K,N_c} \end{bmatrix} \qquad (8)$$

At the receiver side, all the operations will be performed in reverse to that of the transmitter until all the symbols corresponding to one super-frame are not received. Here in our analysis we are using MMSE receiver because of its ability to minimize the overall error caused by noise and mutual interference. Then the reconstructed data signal is obtained as follows (M. Jankiraman, 2004; Y. Cho, *et al,* 2011).

$$\hat{x} = \left(G^H G + \sigma^2 \mathrm{I}\right)^{-1} G^H y \qquad (9)$$

Where $\hat{x} = \left[\hat{x}_1, \hat{x}_2, \ldots\ldots \hat{x}_M\right]$ is the reconstructed signal, G is the channel matrix and y is the received symbol.

In order to proceed further, the value of channel matrix G from equation (7) is substituted in the equation (9). As a result, the reconstructed signal for user 1 can be rewritten as (H. Dahman, *et al,* 2011).

$$\hat{x}_1 = \left(\widehat{H}_1^H \widehat{H}_1 + \sigma^2 \mathrm{I}\right)^{-1} \widehat{H}_1^H y \qquad (10)$$

Where σ^2 is the background noise and I is the identity matrix then substituting the value of equation (5) and (6) in equation (10) we get

$$= \left(\tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_1 + \sigma^2 \mathrm{I}\right)^{-1} \tilde{s}_1^H \widetilde{H}^H \left(\widetilde{H}\tilde{s}_1 x_1 + \widetilde{H}\tilde{s}_2 x_2 + \ldots\ldots \widetilde{H}\tilde{s}_M x_M + n\right)$$

From the above equation we can identify the desired signal S, multiple access interference (MAI) I and noise η which are represented as in (H. Dahman, *et al,* 2011)

$$S = x_1 \qquad (11)$$

$$I = \left(\tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_1 + \sigma^2 \mathrm{I}\right)^{-1} \sum_{k=2}^{M} \left(\tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_k\right) x_k \qquad (12)$$

$$\eta = \left(\tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_1 + \sigma^2 \mathrm{I}\right)^{-1} \tilde{s}_1^H \widetilde{H}^H \, n \qquad (13)$$

For finding the Signal-to-interference noise ratio (SINR) Γ, we assume that S, I, η are uncorrelated therefore,

$$\Gamma = \frac{E[S^2]}{E[|I|^2] + E[|\eta|^2]} \qquad (14)$$

$$= \frac{E[S^2]}{\sigma_I{}^2 + \sigma_\eta{}^2}$$

If x_k(MAI) are assumed to be mutually independent, then input symbols $\{x_k\}_{k=1}^{M}$ are assumed to be Gaussian with unit variance. The effective channel $\widehat{H}_k^H$ is Gaussian random variable with zero mean and unit variance $\sim$CN(0, 1) is denoted as

$$\widehat{H}_k^H \widehat{H}_l = \tilde{s}_k^H \widetilde{H}^H \widetilde{H} \tilde{s}_l \qquad (15)$$

Now Average power of desired signal is taken as

$$E[S^2] = 1 \qquad (16)$$

Further, multiple access interference σ_I^2 can now be rewritten as

$$\sigma_I^2 = E[|I|^2]$$
$$= E[(\tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_1 + \sigma^2 \mathrm{I})^{-2} \sum_{k=2}^{M} |\tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_k|^2 \quad (17)$$

Since $E[x_k]^2 = 1$ and using equation (6) we obtain

$$= E[|\widehat{H}_1^H \widehat{H}_1 + \sigma^2 \mathrm{I}|^{-2} \sum_{k=2}^{M} |\widehat{H}_1^H \widehat{H}_k|^2 \quad (18)$$

Now let's us assume in equation (18) that $\widehat{H}_1 = \sqrt{\widehat{H}_1^H \widehat{H}_1} P e_1$, where P is permutation matrix and e_1 is the 1-st column of the Identity matrix. Then putting the value of above equation in (18) we get

$$\sigma_I^2 = E\left[|\widehat{H}_1^H \widehat{H}_1 + \sigma^2 \mathrm{I}|^{-2} \sum_{k=2}^{M} \left|\sqrt{\widehat{H}_1^H} \widehat{H}_1 e_1^H (P^H \widehat{H}_k)\right|^2\right] \quad (19)$$

$$= E\left[|\widehat{H}_1^H \widehat{H}_1 + \sigma^2 \mathrm{I}|^{-2} |\widehat{H}_1^H \widehat{H}_1| \sum_{k=2}^{M} |e_1^H (P^H \widehat{H}_k)|^2\right] \quad (20)$$

By applying Binomial Theorem in the above equation we get

$$(1+x)^n = 1 + nx \quad for\ x < 1$$

Now taking $|\widehat{H}_1^H \widehat{H}_1|^{-2}$ common in the equation (20) we get

$$= |\widehat{H}_1^H \widehat{H}_1|^{-2} \left[1 + \frac{\sigma^2 \mathrm{I}}{|\widehat{H}_1^H \widehat{H}_1|}\right]^{-2} |\widehat{H}_1^H \widehat{H}_1| \quad (21)$$

Now in equation (21) assume $x = \frac{\sigma^2 \mathrm{I}}{|\widehat{H}_1^H \widehat{H}_1|}$and it is less than 1, so after applying Binomial Theorem we get

$$= (\widehat{H}_1^H \widehat{H}_1)^{-1} \left[1 - \frac{2\sigma^2 \mathrm{I}}{\widehat{H}_1^H \widehat{H}_1}\right] \quad (22)$$

Putting the value of equation (22) in (20) we get

$$= E\left[\left(|\widehat{H}_1^H \widehat{H}_1|^{-1} - 2(\sigma^2 \mathrm{I})|\widehat{H}_1^H \widehat{H}_1|^{-2}\right) \sum_{k=2}^{M} |e_1^H (P^H \widehat{H}_k)|^2\right] \quad (23)$$

$$= E\left[\frac{\sum_{k=2}^{M} |e_1^H (P^H \widehat{H}_k)|^2}{|\widehat{H}_1^H \widehat{H}_1|}\right] - 2(\sigma^2 \mathrm{I}) E\left[|\widehat{H}_1^H \widehat{H}_1|^{-2} \sum_{k=2}^{M} |e_1^H (P^H \widehat{H}_k)|^2\right] \quad (24)$$

Now the above equation can be written as

$$\sigma_I^2 = \frac{\left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2}{\left(\frac{1}{N_t N_C}\right) \sum_{m=1}^{N_t N_c} |\hat{x}_m|^2} - 2(\sigma^2 \mathrm{I}) E\left[|\widehat{H}_1^H \widehat{H}_1|^{-2}\right] \left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2 \quad (25)$$

In the above equation $|\hat{z}_k|^2$ and $|\hat{x}_m|^2$ are the chi-squared random variables, $(M-1)$ and $\left(\frac{1}{N_t N_C}\right)$are the degrees of freedom and $\widehat{H}_k$ is the Gaussian random variable.

Average Noise power is taken as

$$\sigma_\eta^2 = E\left\{(\tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_1 + \sigma^2 \mathrm{I})^{-2} \tilde{s}_1^H \widetilde{H}^H n n^H \widetilde{H} \tilde{s}_1\right\} \quad (26)$$

Putting the value from equation (6) and since $E[nn^H] = \sigma_n^2 \mathrm{I}$ in equation (26) we can get

$$= E\left[|\widehat{H}_1^H \widehat{H}_1 + \sigma^2 \mathrm{I}|^{-2} \tilde{s}_1^H \widetilde{H}^H \widetilde{H} \tilde{s}_1\right] \sigma_n^2 \mathrm{I} \quad (27)$$
$$= E\left[|\widehat{H}_1^H \widehat{H}_1 + \sigma^2 \mathrm{I}|^{-2} |\widehat{H}_1^H \widehat{H}_1|\right] \sigma_n^2 \quad (28)$$

Where I is the identity matrix.

Again by applying Binomial theorem in the above equation we get

$$= E\left[|\widehat{H}_1^H \widehat{H}_1|^{-1} - 2(\sigma^2 \mathrm{I})|\widehat{H}_1^H \widehat{H}_1|^{-2}\right] \sigma_n^2 \quad (29)$$
$$= \frac{\sigma_n^2}{E|\widehat{H}_1^H \widehat{H}_1|} - 2(\sigma^2 \mathrm{I}) E|\widehat{H}_1^H \widehat{H}_1|^{-2} \sigma_n^2 \quad (30)$$

By solving the above equation, as defined in equation (25) we get

$$\sigma_\eta^2 = \frac{\sigma_n^2}{\left(\frac{1}{N_t N_C}\right) \sum_{m=1}^{N_t N_c} |\hat{x}_m|^2} - 2(\sigma^2 \mathrm{I}) E|\widehat{H}_1^H \widehat{H}_1|^{-2} \sigma_n^2 \quad (31)$$

Hence putting the value from equation (16), (25) and (31) in equation (14), we obtain SINR expression for MMSE receiver in MIMO-OFDM-CDMA system as below:

$$= \frac{1}{\frac{\left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2}{\left(\frac{1}{N_t N_C}\right) \sum_{m=1}^{N_t N_c} |\hat{x}_m|^2} + \frac{\sigma_n^2}{\left(\frac{1}{N_t N_C}\right) \sum_{m=1}^{N_t N_c} |\hat{x}_m|^2} - 2(\sigma^2 \mathrm{I}) E|\widehat{H}_1^H \widehat{H}_1|^{-2} \left\{\left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2 + \sigma_n^2\right\}} \quad (32)$$

$$= \frac{1}{(1/F_{a,b}) + (\sigma_n^2/\chi^2) - 2(\sigma^2 \mathrm{I}) E|\widehat{H}_1^H \widehat{H}_1|^{-2} \left\{\left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2 + \sigma_n^2\right\}} \quad (33)$$

Where $\chi^2$is the chi-squared random variable with $N_t N_c$ degree of freedom and $F_{a,b}$ is the F- distribution random variable (which is ratio of two chi-squared random variable) where $a = N_t N_c$ and $b = M-1$ degrees of freedom.

When the number of users increases, then the interference component will be the dominant component i.e.$\left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2 > \sigma^2$, therefore by neglecting σ^2, equation (32) can be rewritten as

$$= \frac{1}{\frac{\left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2}{\left(\frac{1}{N_t N_C}\right) \sum_{m=1}^{N_t N_c} |\hat{x}_m|^2} - 2(\sigma^2 \mathrm{I}) E|\widehat{H}_1^H \widehat{H}_1|^{-2} \left\{\left(\frac{1}{M-1}\right) \sum_{k=2}^{M} |\hat{z}_k|^2\right\}} \quad (34)$$

The BER results can be evaluated from the following equations which are given below:

$$P_e = Q(\sqrt{\Gamma}) \quad (35)$$

$$P_e = erfc(sqrt(SINR)) \quad (36)$$

$$P_e = \int_0^\infty f(y) Q(\sqrt{y}) dy \quad (37)$$

The BER results of MIMO-OFDM-CDMA system for MMSE receiver were obtained through computer simulation using MATLAB software by putting the value of SINR in equation (36).

Performance evaluation

In this section, we will show the simulation results of the derived expression as well as results obtained through computer simulation model. We first describe the system parameters followed by its results.

System Parameters

Both computer simulation and mathematical analysis are carried out to investigate the performance of MIMO-OFDM-CDMA system using MMSE receiver where we assume $N_t = 4$ transmit antennas and $N_r = 4$ receive antennas and channel is assumed to be Rayleigh fadingwith channel length of L=4. For Time and Space spreading, Walsh-Hadamard codes are being used and the length of the spreading code is $N_C = 16$ and where each OFDM symbols has 128 subcarriers. The modulation technique used is quadrature phase-shift keying (QPSK) and the maximum number of users allowed by the system is $N_C(\min N_t N_r))$ as in (H. Dahman, *et al,* 2011).

Results

In figure 2, we have plotted the probability density function (pdf) for SINR of MIMO-OFDM-CDMA system using MMSE receiver. The curve is obtained by the computer programming of SINR expression from equation (32) obtained through detailed mathematical analysis. It has been observed from the figure that the peak value of pdf of SINR is at 0.47 at SINR of 23dB.

Further, figure 3 shows the PDF curves of SINR for various numbers of users i.e. 8, 16, 32 and 64 users and it has been observed from the figure that the SINR PDF curve for user 8 has higher value than 16, 32 and 64 users.

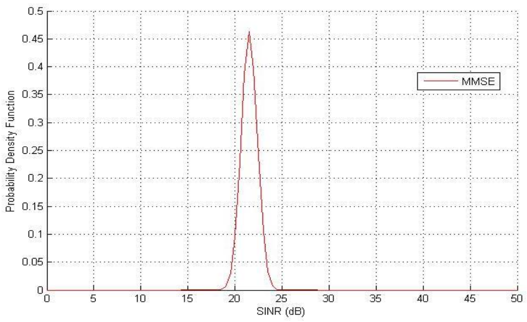


Fig. 2: Probability density function of SINR for MIMO-OFDM-CDMA system using MMSE

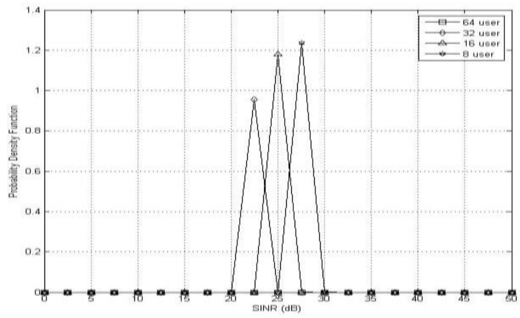


Fig. 3: Probability density functions of SINR for MIMO-OFDM-CDMA system with different number of users

Hence it is found that as the number of users increases, the peak SINR decreases. Figure 4 shows the BER performance of MIMO-OFDM-CDMA system with different number of users (2, 8, 16 and 32) in Rayleigh fading channel. These curves are obtained by computer programming of BER expression obtained from equation (32) and (36) through detailed mathematical analysis. It is clear from the figure (4) that the BER performance is degraded, as the number of users increases. For instance, at SNR of 8 dB, the BER values are 6e-6, 1e-5, 3e-5 and 5e-4 for 2, 8, 16 and 32 users respectively. The results incorporated in this figure include the effects of both MAI as well as noise.

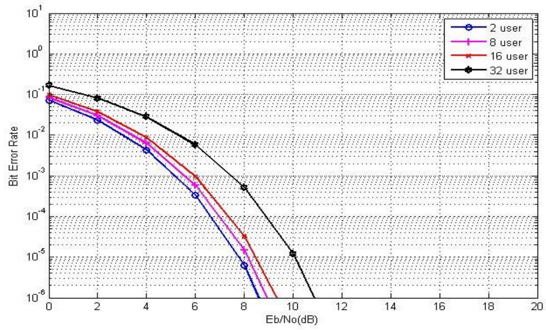


Fig. 4: BER Performance of MIMO-OFDM-CDMA system in Rayleigh fading channel using $4T_x$and $4R_x$ antennas.

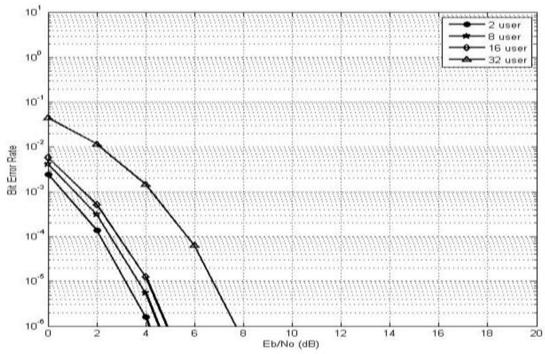


Fig. 5: BER performance of MIMO-OFDM-CDMA system using $4T_x$and $4R_x$ antennas, when only MAI is considered

Figure 5 shows the BER performance of MIMO-OFDM-CDMA system, with different numbers of users in the channel when only MAI is only considered. The curves are obtained by computer programming of BER expression obtained by putting the value of equation (34) in equation (36).

It is clear from the figure 5 that the BER performance degrades as the number of users is increased. For example, at SNR of 4 dB, the BER values are 2e-6, 5e-6, 1e-5 and 2e-3 for 2, 8, 16 and 32 users respectively and the results show a great improvement as compared to the BER performance of MIMO-OFDM-CDMA system in Rayleigh fading channel as shown in figure 4.

Further, figure 6 shows the comparative BER performance of MIMO-OFDM-CDMA system with respect to MMSE and ZF receiver for different number of users in Rayleigh fading channel. The solid lines in the figure represent MMSE receiver results, while dotted lines represent the ZF receiver results as proposed in (H. Dahman, *et al,* 2011). It is clear from the figure that the MMSE receiver performs better than ZF receiver in all cases.

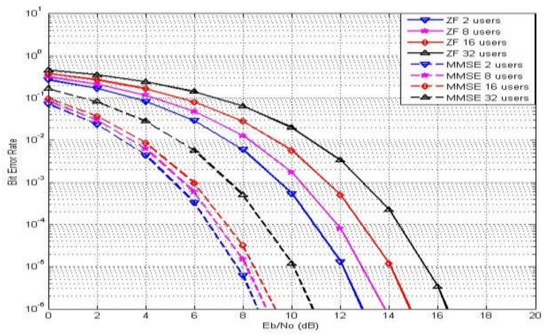


Fig. 6: Comparative BER Performance of MIMO-OFDM-CDMA system with respect to MMSE and ZF receiver in Rayleigh fading channel

Lastly, in figure 7, we compare the analytical result provided by the equation (32) with the simulation model of MIMO-OFDM-CDMA system using MMSE receiver. It is interesting to note that the simulation results are in line with our analytically derived results provided all the system parameters are same.

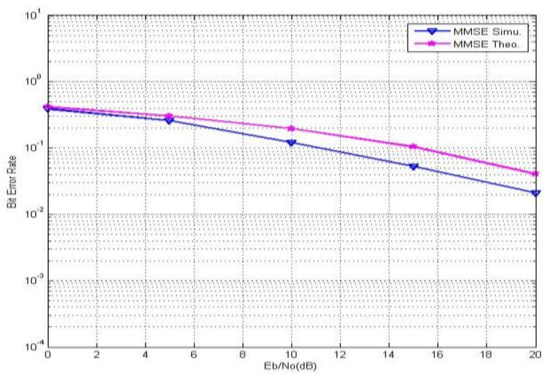


Fig. 7: Probability of error for MIMO-OFDM-CDMA system using MMSE receiver (Analytical vs. Simulation model)

Conclusion

In this paper, the space, time and frequency spread MIMO-OFDM-CDMA system using MMSE receiver has been considered. The accurate expressions for SINR have been derived through detailed mathematical analysis. Further, the probability of error results has been presented in detail and compared with that of ZF receiver. MMSE receiver is mainly considered in this system because it considers background noise and does not allow noise enhancement as compared to other receivers. The PDF curves for the derived output SINR expressions show that the peak SINR decreases as the number of users is increased from 8 to 64. The comparative results of ZF and MMSE receiver in terms of BER show that MMSE receiver performs always better than ZF receiver. The simulation results are well in line with the analytically derived results.

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