PERFORMANCE OF ASYNCHRONOUS MULTIPLE ACCESS MIMO OFDM SYSTEMS

Hyejung Jung and Michael D. Zoltowski

School of Electrical and Computer Engineering,
Purdue University,
West Lafayette, IN 47907-2035
{jungh, mikedz}@ecn.purdue.edu

ABSTRACT

This paper investigates the performance of orthogonal frequency division multiplexing (OFDM) based asynchronous multiple access multiple input multiple output channels. In an asynchronous mode of data transmission, independent decoding without user cooperation is a more appropriate approach. Thus, various suboptimal transmitter diversity techniques such as space-time block coding and beamforming are employed, and their performances are evaluated. The average signal to interference and noise ratio (SINR) resulting from linear minimum mean squared error (MMSE) combining is exploited to compute symbol error rate. Simulation results demonstrate that space-time block coding hardly achieves substantial transmitter diversity gains in asynchronous channels. Moreover, receiver diversity is an important factor of the overall performance in a large system. However, beamforming, which uses only part of existing spatial dimensions, can improve the bit- and symbol-error rate performance in the low signal-to-noise ratio (SNR) region where practical communication systems are operated.

1. INTRODUCTION

Multiple input multiple output (MIMO) systems equipped with multiple transmit and receive antennas are known to increase the link capacity in wireless communication channels [1]. As wireless communication is challenged by limited spectral resources, frequency reuse and multi-user multiplexing have drawn a lot of attention. Recently, [2] demonstrates that multi-user MIMO systems can have better performance in terms of maximum throughput than time division multiple access based schemes via transmit signal processing if the number of transmit antennas is much larger than the number of receive antennas. Closed-loop based various transmission schemes, which effectively reduce the co-channel interference, are proposed for multi-user MIMO broadcast channels [3]. However, in uplink multiple access channels without timing synchronization among different users, data streams from multiple transmit antennas may cause high-level co-channel interference. In addition, channel and timing knowledge for other users is usually not available at transmitters in uplink channels.

The goal of this work is to demonstrate how much performance gain can be achieved by simple and practically feasible transmitter diversity techniques in asynchronous multi-user OFDM channels. In the considered multi-user OFDM system, each user is allowed to occupy all existing subchannles, and a given spectrum band is shared by multiple users at the same time. An adaptive antenna array is employed at the receiver for separation of multiple-source signal. As for synchronous multi-user MIMO OFDM channels, a linear receiver which jointly performs space-time decoding and interference suppression in frequency-flat fading channels [4] can be directly applied on a per-carrier basis. However, detection techniques and effect of transmit diversity techniques are hardly known for asynchronous multi-user MIMO OFDM systems. In this paper, the performance of spatially multiplexed asynchronous multi-user MIMO OFDM systems is studied over both open- and closed-loop transmit diversity techniques.

The rest of the paper proceeds as follows. Section 2 and Section 3 describe a signal model and an MMSE detection scheme for asynchronous multi-user MIMO OFDM systems, respectively. Section 4 derives an expression of mutual information and evaluates symbol error rate numerically, and Section 5 concludes the paper. Finally, note that $(\cdot)^T$, $(\cdot)^H$, and $(\cdot)^*$ denote the transpose, conjugate transpose, and element-wise conjugate operator, respectively.

2. SYSTEM DESCRIPTION

Consider an asynchronous uplink channel that U active users transmit OFDM signals simultaneously on the same frequency band without timing synchronization. Each user is equipped with M_t multiple transmitting antennas, and a base station or an access point employs M_r receiving antennas. The number of receiving anntennas, M_r, is assumed to be equal to or larger than the number of active users, U, which guarantees the separation of multiple source signals.

The information bit sequence $\{d^{(u)}\}$ for each user u is encoded by a convolutional code encoder, and the coded bit sequence $\{b^{(u)}\}$ passes through an interleaver. After the interleaved bits are assigned to constellation points, the resulting symbols are passed to a space-time processor which performs various transmitter diversity techniques. Let

$$\ldots\ \mathbf{X}^{(u)}(n_b-1),\ \mathbf{X}^{(u)}(n_b),\ \mathbf{X}^{(u)}(n_b+1),\ \ldots \tag{1}$$

be a data stream of user u, which results from bit-interleaved coded modulation. Suppose that an OFDM system processes a block of K symbols at a time. Then, the n_b-th block of frequency domain data for user u, $\mathbf{X}^{(u)}(n_b)$, is given by

$$\mathbf{X}^{(u)}(n_b) = \left[X^{(u)}(0,n_b),\ldots,X^{(u)}(K-1,n_b)\right]^T, \tag{2}$$

where subsymbols $\{X^{(u)}(k,n_b)\}_{k=0}^{K-1}$ are assumed to be independent with zero mean. Using the data stream (1), the space-time processor generates a set of multiple data streams $\{S^{(u,i)}(k,n_b)\}$ for M_t transmitting antennas, where $u \in \{1, \ \ldots\ U\}$ and $i \in \{1, \ \ldots\ M_t\}$.

OFDM modulation at each transmit antenna consists of serial-to-parallel conversion, an inverse fast Fourier transform (IFFT), and parallel-to-serial conversion. The IFFT/FFT size N is assumed to be greater than K since practical OFDM systems have null side carriers as a frequency guard band. To overcome multi-path fading, the cyclic prefix of length L_{cp}, which is equal to or greater than the maximum delay spread L minus one, is appended to the beginning of a vector $\mathbf{s}^{(u,i)}[n_b]$, the IFFT output of the n_b-th data block $\mathbf{S}^{(u,i)}(n_b)$. Subsequent blocks of time-domain OFDM samples are transmitted over wireless channels.

At a receiver, let $\mathbf{y}_m^{(u)}[n_b]$ be an $N \times 1$ received signal vector at receiving antenna m synchronized to the n_b-th OFDM baud of user u. Note that $\mathbf{y}_m^{(u)}[n_b]$ is obtained by removing first L_{cp} samples corresponding to the cyclic prefix. The different distances from each user to the receiver cause the signals to arrive asynchronously. Therefore, we denote the interfering user u's timing offset relative to the beginning of the desired user's cyclic prefix as $L_d^{(u)}$. Without loss of generality, user 1 is assumed to be the desired user, and $L_d^{(1)} \leqslant L_d^{(2)} \leqslant \cdots \leqslant L_d^{(U)}$ with $L_d^{(1)} = 0$. From now on, the superscript of $\mathbf{y}_m^{(1)}[n_b]$ will be omitted for the simplicity of notation.

To detect symbols transmitted from the desired user, we define an $M_r N \times 1$ demodulated signal vector $\mathbf{Y}(n_b)$ as follows:

$$\mathbf{Y}(n_b) = \sum_{u=1}^{U} \mathbf{A}^{(u)} \mathbf{S}^{(u)} + \mathbf{V}, \tag{3}$$

where $\mathbf{Y}(n_b) = \begin{bmatrix} \mathbf{Y}_1(n_b)^T & \ldots & \mathbf{Y}_{M_r}(n_b)^T \end{bmatrix}^T$, where $\mathbf{Y}_m(n_b)$ is the $N \times 1$ FFT output vector of $\mathbf{y}_m[n_b]$, $\mathbf{V}$ denotes block of frequency-domain Gaussian noise samples, and block of transmitted data $\mathbf{S}^{(u)}$ is given by

$$\mathbf{S}^{(u)} = \begin{bmatrix} \mathbf{S}^{(u,1)T} & \ldots & \mathbf{S}^{(u,M_t)T} \end{bmatrix}^T,$$

where

$$\mathbf{S}^{(u,i)} = \begin{cases} \mathbf{S}^{(u,i)}(n_b), & L_d^{(u)} = 0; \\ \begin{bmatrix} \mathbf{S}^{(u,i)}(n_b - 1)^T & \mathbf{S}^{(u,i)}(n_b)^T \end{bmatrix}^T, & \text{otherwise.} \end{cases}$$

The matrix $\mathbf{A}^{(u)}$ in (3) is given by

$$\mathbf{A}^{(u)} = \begin{bmatrix} \mathbf{F}_N \boldsymbol{\mathcal{H}}_1^{(u,1)} \mathbf{F}^{(u)} & \cdots & \mathbf{F}_N \boldsymbol{\mathcal{H}}_1^{(u,M_t)} \mathbf{F}^{(u)} \\ \vdots & \vdots & \vdots \\ \mathbf{F}_N \boldsymbol{\mathcal{H}}_{M_r}^{(u,1)} \mathbf{F}^{(u)} & \cdots & \mathbf{F}_N \boldsymbol{\mathcal{H}}_{M_r}^{(u,M_t)} \mathbf{F}^{(u)} \end{bmatrix}, \tag{4}$$

where the matrix $\mathbf{F}_N$ represents N-point discrete Fourier transform normalized by $\sqrt{N}$, $\boldsymbol{\mathcal{H}}_m^{(u,i)}$ is an $N \times (N + L - 1)$ channel filtering matrix constructed by $h_m^{(u,i)}[n]$, a channel impulse response between user u's transmitting antenna i and receiving antenna m, and OFDM modulation matrix $\mathbf{F}^{(u)}$ is defined same as in [5]. The matrix $\mathbf{F}_N \boldsymbol{\mathcal{H}}_m^{(u,i)} \mathbf{F}^{(u)}$ is of size $N \times K$ if the user u has no relative timing offset. In contrast, it is an $N \times 2K$ matrix for the asynchronous user since performing FFT with timing mismatch induces the inter-block interference.

MMSE diversity combining over time-domain samples from all receiving antennas, which is called space-time MMSE, was presented in [5] for asynchronous interference suppression in multi-user single transmit antenna OFDM channels. It can be easily shown that space-time MMSE detection is equivalent to frequency-domain MMSE combining, which exploits FFT output samples across all subcarriers, in terms of mean squared error performance. In this paper, frequency-domain signal representation and processing are employed for the convenience of analysis of beamforming techniques in the following section.

3. ASYNCHRONOUS MULTIPLE ACCESS MIMO OFDM

This section discusses multiple antenna transmission schemes, which especially focus on beamforming, and develops a linear MMSE receiver for asynchronous multi-user MIMO OFDM. Sum capacity achieving transmission policies have not yet been investigated for asynchronous multi-user MIMO channels. Although an iterative multi-user waterfilling algorithm has been proposed for synchronous multiple access channels [6], joint decoding and user cooperation exploiting other users' channel state information are not practically feasible for uplink channels with random timing offset. In this paper, per-carrier based one dimensional beamforming is employed from the insight in [7] that each user in multi-user environments should not use too many dimensions for achieving the sum capacity. The beamforming technique applied to this paper selects a beamforming vector for each user and each subcarrier independently without considering the overall multiple access interference level.

In order to express per-carrier based transmitter diversity processing efficiently, samples in the vector $\mathbf{Y}(n_b)$ are reordered, and (3) can be rewritten as follows:

$$\overline{\mathbf{Y}}(n_b) = \sum_{u=1}^{U} \overline{\mathbf{A}}^{(u)} \overline{\mathbf{S}}^{(u)} + \overline{\mathbf{V}}, \tag{5}$$

where $\overline{\mathbf{Y}}(n_b) = \begin{bmatrix} \mathbf{Y}(0, n_b)^T & \ldots & \mathbf{Y}(K-1, n_b)^T \end{bmatrix}^T$, where $\mathbf{Y}(k, n_b) = [Y_1(k, n_b) \ \ldots \ Y_{M_r}(k, n_b)]^T$, and the matrix $\overline{\mathbf{A}}^{(u)}$ is formed by rearranging elements of $\mathbf{A}^{(u)}$ and given by

$$\overline{\mathbf{A}}^{(u)} = \begin{bmatrix} \overline{\mathbf{A}}_{0,0}^{(u)} & \cdots & \overline{\mathbf{A}}_{0,K-1}^{(u)} \\ \vdots & \vdots & \vdots \\ \overline{\mathbf{A}}_{N-1,0}^{(u)} & \cdots & \overline{\mathbf{A}}_{N-1,K-1}^{(u)} \end{bmatrix}, \tag{6}$$

where the submatrix $\overline{\mathbf{A}}_{n,k}^{(u)}$ is of size $M_r \times M_t$ for the synchronous user and of $M_r \times 2M_t$ for the asynchronous user. Accordingly, $\overline{\mathbf{S}}^{(u)} = \begin{bmatrix} \overline{\mathbf{S}}^{(u)}(0, n_b)^T & \ldots & \overline{\mathbf{S}}^{(u)}(K-1, n_b)^T \end{bmatrix}^T$ for the synchronous user and, if $L_d^{(u)} \neq 0$, $\overline{\mathbf{S}}^{(u)}$ is defined as

$$\overline{\mathbf{S}}^{(u)} = \Big[\overline{\mathbf{S}}^{(u)}(0, n_b - 1)^T \ \overline{\mathbf{S}}^{(u)}(0, n_b)^T \ \ldots \tag{7}$$
$$\ldots \ \overline{\mathbf{S}}^{(u)}(K-1, n_b - 1)^T \ \overline{\mathbf{S}}^{(u)}(K-1, n_b)^T \Big]^T,$$

where $\overline{\mathbf{S}}^{(u)}(k, n_b) = \begin{bmatrix} S^{(u,1)}(k, n_b) \ \ldots \ S^{(u,M_t)}(k, n_b) \end{bmatrix}^T$.Without loss of generality, it is assumed that OFDM symbols are modulated from subcarrier 0 to subcarrier $K - 1$. If the channel state is time-invariant over one OFDM symbol interval, then the submatrix $\overline{\mathbf{A}}_{n,k}^{(u)}$ for the synchronous user is given by

$$\overline{\mathbf{A}}_{n,k}^{(u)} = \begin{bmatrix} H_1^{(u,1)}(k, n_b) & \cdots & H_1^{(u,M_t)}(k, n_b) \\ \vdots & \ddots & \vdots \\ H_{M_r}^{(u,1)}(k, n_b) & \cdots & H_{M_r}^{(u,M_t)}(k, n_b) \end{bmatrix}; \ n = k, \tag{8}$$

where $H_m^{(u,i)}(k, n_b)$ is a channel gain of the link between user u's antenna i and receiving antenna m at subchannel k. If $n \neq k$, then $\overline{\mathbf{A}}_{n,k}^{(u)} = \mathbf{0}$. That is, there is no inter-carrier interference for the synchronous user.

When the transmitter has the information on its own channels, the beamforming vector of user u at subcarrier k, $\mathbf{p}^{(u)}(k, n_b)$, is obtained from the dominant right singular vector of an $M_r \times M_t$ channel gain matrix. If channels are correlated at the transmitter side and an $M_t \times M_t$ transmit antenna correlation matrix is only known, the dominant eigenvector of the correlation matrix is selected as a beamforming vector [8]. The latter is called statistical beamforming. After beamforming operation, the space-time processor outputs the vector $\overline{\mathbf{S}}^{(u)}(k, n_b) = \mathbf{p}^{(u)}(k, n_b)X(k, n_b)$ at each subchannel k.

The space-frequency MMSE filter $\mathbf{W}_{\text{BF}}$ of size $K \times NM_r$ for detection of $\mathbf{X}^{(1)}(n_b)$ can be derived from (5). Assuming that no correlation exists among different users' data, $\mathbf{W}_{\text{BF}}$ is given by

$$\mathbf{W}_{\text{BF}} = \mathbf{R}^{(1)}_{\mathbf{XX}} \overline{\mathbf{A}}^{(1)^H}_{\text{BF}} \left(\overline{\mathbf{A}}^{(1)}_{\text{BF}} \mathbf{R}^{(1)}_{\mathbf{XX}} \overline{\mathbf{A}}^{(1)^H}_{\text{BF}} + \mathbf{R}_{\text{IN}} \right)^{-1}, \quad (9)$$

where the matrix $\mathbf{R}^{(u)}_{\mathbf{XX}}$ is an autocorrelation matrix of $\mathbf{X}^{(u)}$, the matrix $\overline{\mathbf{A}}^{(1)}_{\text{BF}}$ of size $NM_r \times K$ is obtained by multiplying each submatrix $\overline{\mathbf{A}}^{(1)}_{n,k}$ by the beamforming vector $\mathbf{p}^{(1)}(k, n_b)$, and

$$\mathbf{R}_{\text{IN}} = \sum_{u=2}^{U} \overline{\mathbf{A}}^{(u)} \mathbf{R}^{(u)}_{\overline{\mathbf{SS}}} \overline{\mathbf{A}}^{(u)^H} + \mathbf{R}_{\overline{\mathbf{VV}}}. \quad (10)$$

The MMSE filter output $\mathbf{Z}(n_b)$ given by $\mathbf{Z}(n_b) = \mathbf{W}_{\text{BF}}\overline{\mathbf{Y}}(n_b)$ passes through a log likelihood ratio computation block followed by a soft Viterbi decoder.

4. PERFORMANCE EVALUATION

In this section, performance functions which can characterize the performance of a large system are derived, and symbol and bit error rates are evaluated via both numerical computation and Monte Carlo simulation.

4.1. Performance Analysis

In order to analyze the effect of MMSE filtering, the MMSE filter output $\mathbf{Z}(n_b)$ is rewritten as

$$\mathbf{Z}(n_b) = \tilde{\mathbf{A}}\mathbf{X}^{(1)}(n_b) + \tilde{\mathbf{V}}, \quad (11)$$

where the vector $\tilde{\mathbf{V}}$ represents the filtered interference plus noise and $\tilde{\mathbf{A}} = \mathbf{W}_{BF}\mathbf{A}^{(1)}_{\text{BF}}$. Then, by definition, the correlation matrix of $\mathbf{Z}(n_b)$, $\mathbf{R}_{\mathbf{ZZ}}$, can be expressed as

$$\mathbf{R}_{\mathbf{ZZ}} = \mathbf{W}_{\text{BF}} \mathbf{R}_{\overline{\mathbf{YY}}} \mathbf{W}^H_{\text{BF}} = \tilde{\mathbf{A}} \mathbf{R}^{(1)}_{\mathbf{XX}}. \quad (12)$$

Assuming that transmitted symbols $\{X(k, n_b)\}$ are independent, diagonal elements of the matrix $\tilde{\mathbf{A}}$ are real and positive from the definition of $\tilde{\mathbf{A}}$. Then, the post-filtering average SINR at each subchannel k can be expressed by $\text{SINR}_k = \frac{a_k}{1-a_k} = -1 + \frac{1}{1-a_k}$, where a_k is the k-th diagonal element of the matrix $\tilde{\mathbf{A}}$.

Assuming independent decoding for each user, the mutual information in asynchronous multi-user OFDM channels is given by

$$\begin{aligned} \mathbf{I}(\overline{\mathbf{Y}}(n_b); \mathbf{X}^{(1)}(n_b)) &= H(\overline{\mathbf{Y}}(n_b)) - H(\overline{\mathbf{Y}}(n_b)|\mathbf{X}^{(1)}(n_b)) \\ &= \log_2 \det(\mathbf{I} + \overline{\mathbf{A}}^{(1)}_{\text{BF}} \mathbf{R}^{(1)}_{\mathbf{XX}} \overline{\mathbf{A}}^{(1)^H}_{\text{BF}} \mathbf{R}^{-1}_{\text{IN}}). \quad (13) \end{aligned}$$

Similarly, the mutual information after linear MMSE processing is

$$\begin{aligned} &\mathbf{I}(\mathbf{Z}(n_b); \mathbf{X}^{(1)}(n_b)) \\ &= \log_2 \det(\mathbf{I} + \tilde{\mathbf{A}}\mathbf{R}^{(1)}_{\mathbf{XX}} \tilde{\mathbf{A}}^H (\tilde{\mathbf{A}}\mathbf{R}^{(1)}_{\mathbf{XX}} - \tilde{\mathbf{A}}\mathbf{R}^{(1)}_{\mathbf{XX}} \tilde{\mathbf{A}}^H)^{-1}) \\ &= \log_2 \det(\mathbf{I} - \tilde{\mathbf{A}}^H)^{-1}. \quad (14) \end{aligned}$$

It can be easily shown that (14) is equal to (13) by using the matrix inversion lemma. Since the MMSE filter does not induce significant amount of self inter-carrier interference, off-diagonal terms of $\tilde{\mathbf{A}}$ are negligible. Hence, from (14), the mutual information in asynchronous multi-user OFDM channels is approximately given by $\sum_{k=0}^{K-1} \log_2\{1/(1-a_k)\} = \sum_{k=0}^{K-1} \log_2\{1+\text{SINR}_k\}$. Meanwhile, it is well known that symbol error rate (SER) is a decreasing function of SINR. Hence, we will present SER performance in the following subsection, which also approximately characterizes mutual information performance.

4.2. Simulation Results

The OFDM system parameters used for simulation are as follows: The size of IDFT/DFT is $N = 64$, and the number of used subcarriers is $K = 49$. The basestation employs as many receive antennas as the number of active users, and each user is equipped with two transmit antennas. The received signal power from each user is equal. The cyclic prefix length is set as $L_{cp} = 16$. Simulations are performed over slowly time-varying Rayleigh fading channels specified as the channel model A in [9]. Correlated MIMO fading channels are generated for statistical beamforming using the exponential transmit correlation model of correlation coefficient $\rho = 0.7$, and independent MIMO channels are used for other diversity techniques. A channel code used in this paper is the half-rate, constraint length seven convolutional code, and bit streams are mapped to 16-QAM constellation points.

Figure 1 presents BER comparison of various transmitter diversity techniques such as space-time block coding (STBC), beamforming (BF), and STBC combined with precoding under two-user asynchronous channels. As for STBC, per-carrier based Alamouti space-time coding is applied, and MMSE detection is performed over $2NM_r$ samples exploiting the Alamouti decoding structure. Note that statistical BF or BF with perfect channel state information (CSI) yields $2 \sim 3$ dB SNR gains over the single transmit antenna system. However, the curves for STBC and STBC combined with precoding have an error floor in the high SNR region. Figure 1 shows that the inherent property of space-time block codes, that is, coding across several OFDM bauds, induces more interference than BF techniques in asynchronous channels.

SER of two-user asynchronous channels is given in Figure 2. The solid lines are obtained via Monte Carlo simulation, and the dotted lines via numerical computation of the SER expression [10]. Figure 2 shows that there is no significant performance difference between Monte Carlo simulation and numerical computation. Hence, the SER expression is used for the following figures. Figure 3 also demonstrates SER when four active users exist. Interestingly, in Figure 3, statistical BF has the lowest SER, and the single transmit antenna system outperforms BF with perfect CSI in the high SNR region. In addition, note that statistical BF outperforms BF with perfect CSI in Figure 4 as the number of active users and, accordingly, the number of receive antennas increase. In a single user MIMO system, it is known that the channel capacity for correlated fading channels is less than for independent MIMO channels. However, Figure 3 and Figure 4 imply that a greedy approach that each user uses its own best channel with high degree of freedom is not an effective transmission policy for asynchronous multiple access channels.

5. CONCLUSION

This paper presents the performance characteristic of asynchronous multi-user MIMO OFDM systems. In contrast to single user MIMO

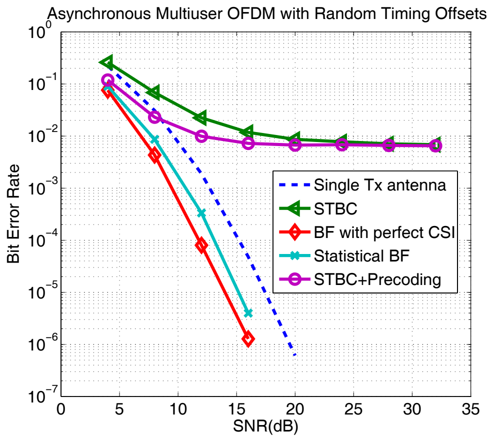

Fig. 1. Coded BER comparison of various transmitter diversity techniques in a two-user OFDM system

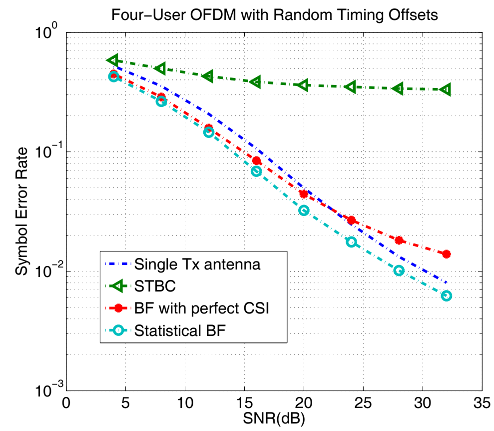

Fig. 3. Analytic SER when four active users and four receiving antennas exist

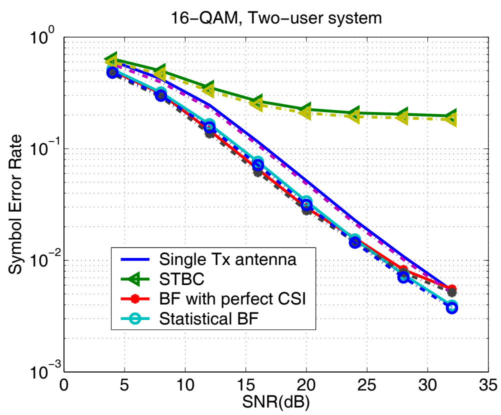

Fig. 2. Analytic and experimental SER performance comparison in a two-user OFDM system

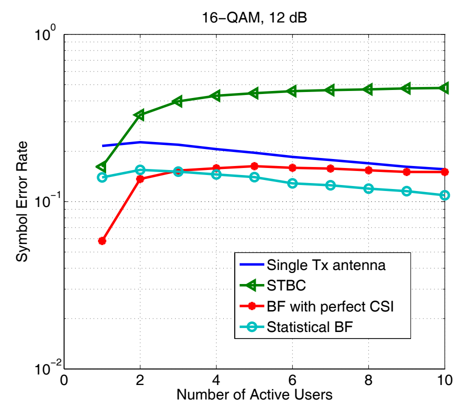

Fig. 4. Number of active users vs SER at 12 dB SNR

systems, if the number of active users is large, statistical beamforming in correlated fading channels yields lower SER than beamforming in independent MIMO channels. The results shown in this paper motivate studies on optimal transmission algorithms for asynchronous multiple access channels.

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