# BER OPTIMIZED UNIMODE PRECODER DESIGN FOR MIMO-OFDM BASED SPATIAL MULTIPLEXING SYSTEMS

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## ABSTRACT

A bit error rate optimized unimode selection algorithm is proposed for MIMO-OFDM based spatial multiplexing systems using linear receivers. For a fixed number of antennas, the proposed scheme dynamically selects the number of subcarriers used for transmission. The proposed method increases the diversity advantage of spatial multiplexing systems without the use of computational expensive space-time receivers such as ML and VBLAST. Simulation results show that the proposed unimode technique outperforms existing ones in terms of link reliability by performing selection of data streams across different subcarriers, and compensating significantly attenuated subcarriers due to deep fades.

***Index Terms***— MIMO-OFDM, antenna selection, unimode precoder, power allocation

## 1. INTRODUCTION

Multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) has been extensively promoted as key technology for next generation of wireless communication systems due to its potential to achieve significant capacity and diversity gain in frequency-selective fading channels without sacrificing spectral efficiency nor incurring heavy computational burden [1]. This capacity gain can however be offset by spatial correlation among the antennas, especially at the mobile terminal where limited space imposes a severe constraint on the placement of the antennas.

Antenna selection has been proposed as an effective and inexpensive means to combat against this problem as it reduces the number of RF chains at the transceiver while retaining many of the diversity benefits. The selection procedure often relies on channel state information (CSI) feedback from the receiver to transmitter [2]–[4]. Technique that only requires training sample sequence was also proposed in [5]. It was shown in [6] that space-time coded MIMO-OFDM can attain full diversity of $L_hN_tN_r$, where each term is denoted as the channel length, number of transmit antenna, and number of receive antennas, respectively. [6] has further shown that employing antenna selection does not change this diversity advantage. This fact has motivated various selection schemes [7]–[9] for MIMO-OFDM based systems. [7] extended the maximum capacity unimode antenna selection scheme (unimode antenna selection schemes only entail selection of the antenna subset in which the number of antenna to be selected is known a priori) in [4] to select a subset of the total number of transmit and receive antennas for transmission by successive eliminating the columns/rows of the channel matrix that yields the minimum loss in capacity. This scheme, however, does not yield the best bit error rate (BER) performance nor does it guarantee the maximum diversity order can be achieved. The multimode scheme in [9] exploit space-frequency block coding, adaptive modulation, and an energy-based antenna selection scheme to further enhance performance. However, the methods do not guarantee optimal BER can be attained as the design scheme does not directly optimizes the BER expression. [8] proposed a minimum mean-squared error (MMSE) based selection scheme which utilized similar successive elimination concept as in [4], [7]. However, it suffers from the same deficiency as [9] in terms of BER optimization. Furthermore, it is unclear what data rate each data stream should have after the selection has been done. While the above techniques assumed a fixed amount of antennas are to be selected, [10] relaxed this constraint and proposed a joint transmit and receive (Tx/Rx) MMSE selection scheme to reduce the BER. Significant improvements in BER performance was reported over conventional MMSE joint Tx/Rx design such as [11] which uses a fixed number of antennas. Unfortunately, the global optimal solution was found only via an exhaustive search. This was acceptable since [10] only considered flat fading MIMO channels with small number of antenna elements.

Herein, a unimode transmit antenna selection/precoding algorithm is proposed for MIMO-OFDM based spatial multiplexing systems. The proposed unimode precoding algorithm is designed to optimize average BER over all data streams under a constant rate constraint by choosing the appropriate mapping of the data stream to the selected antennas (and therefore its corresponding subcarriers) for transmission. The present scheme is able to choose the strongest spectral channels such that the BER is minimized and can easily tradeoff between diversity and spatial multiplexing gain, as discussed in [12]. This is realized by only employing linear receivers, such as zero-forcing (ZF) or MMSE, for signal recovery, thus bypassing the use of computational expensive receivers such as maximum likelihood receivers. Furthermore, the proposed scheme, although suboptimal, is able to achieve good BER performance without resorting to computational expensive waterfilling approach such as [13], which utilizes a greedy algorithm to satisfy a bit rate constraint while minimizing the transmission power.

Results will show that the proposed method can outperform the method proposed by [8] and the OFDM implementation of the methods proposed by [14], [15]. Furthermore, simulation results will indicate that increased diversity order can be achieved compared to those reported in [8], [14], [15] by exploiting spatial and channel gain diversity since the

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number of subcarriers and the mapping of the data stream to those selected antennas and subcarriers are adjusted adaptively based on CSI feedback.

The paper is organized as follows. Section 2 describes the system model. The proposed schemes are developed in Section 3 followed by simulation results in Section 4. The paper will be concluded in Section 5.

*Notation*: Upper (lower) bold face letters indicate matrices (column vectors). Superscript $^H$ denotes Hermitian, $^T$ denotes transposition, $^\dagger$ denotes the Moore-Penrose inverse. $E[\cdot]$ stands for statistical expectation of the entity inside the square bracket. $\mathbf{I}_N$ denotes an $N \times N$ identity matrix. $[\mathbf{A}]_{ii}$ denotes the $i^{th}$ diagonal element of the matrix $\mathbf{A}$. $\sigma_i(\mathbf{A})$ is the $i^{th}$ singluar value of $\mathbf{A}$ arranged in descending order.

## 2. SYSTEM MODEL

Consider a MIMO-OFDM system with $N_t$ transmit antennas, $N_r$ receive antennas and $N_c$ subcarriers. The data symbols of each antenna are modulated with $M$-QAM constellation and converted to block symbols before transmission over frequency-selective fading channels. It shall be assumed that the transmission efficiency due to the cyclic prefix of length $N_{cp}$ for each OFDM symbol of length $N_c$ is defined as $\eta \triangleq \frac{N_c}{N_c+N_{cp}}$. Each subcarrier can be regarded as an independent MIMO flat fading channel due to the orthogonality among subcarriers. The channel matrix $\mathbf{H}(k) \in \mathbb{C}^{N_r \times N_t}$ for the $k^{th}$ subcarrier is

$$\mathbf{H}(k) = \begin{bmatrix} H_{1,1}(k) & H_{1,2}(k) & \cdots & H_{1,N_t}(k) \\ H_{2,1}(k) & H_{2,2}(k) & \cdots & H_{2,N_t}(k) \\ \vdots & \vdots & \ddots & \vdots \\ H_{N_r,1}(k) & H_{N_r,2}(k) & \cdots & H_{N_r,N_t}(k) \end{bmatrix},$$

where $H_{i,j}(k)$ denotes the channel gain between the $j^{th}$ transmit antenna and $i^{th}$ receive antenna for the $k^{th}$ subcarrier. Assuming CSI is known at the receiver. The joint antenna and subcarrier selection can be performed at the receiver and only the indices of the selected antennas are fed back to the transmitter so to reduce feedback overhead. If adaptive power allocation is employed, extra data are required in the feedback to provide power allocation information to the transmitter. In the sequel, it is assumed that coherence time of the channel is large enough for accurate CSI to be fed back to the transmitter.

The transmit antenna selection is performed subcarrier by subcarrier to select $M_t$ transmit antennas out of $N_t$ transmit antennas for the $k^{th}$ subcarrier, where $M_t \leq N_r$ is assumed to avoid rank deficiency when linear receiver is employed. Hence, there are $M_t$ data streams transmitted for all subcarriers. This selection can be done by precoding the transmit data stream by an $N_t \times M_t$ precoding matrix, $\mathbf{W}_{M_t,n(k)}$, which is created by choosing $M_t$ columns from $\mathbf{I}_{N_t}$ for all $k$. $n(k) = 0, 1, \ldots, \begin{pmatrix} N_t \\ M_t \end{pmatrix} - 1$ is the index for the data stream-to-antenna mapping. Thus, the precoder is used to map the data stream to specific antennas prior to transmission. Furthermore, $\mathscr{W}_{M_t} = \left\{\mathbf{W}_{M_t,0}, \ldots, \mathbf{W}_{M_t,\binom{N_t}{M_t}-1}\right\}$ denotes the set containing the precoding matrices $\mathbf{W}_{M_t,n(k)}$. For $M_t = 0$, $\mathscr{W}_0 \triangleq \{\mathbf{W}_{0,0}\}$, where $\mathbf{W}_{0,0}$ denotes an empty matrix, which implies no transmission.

Using the precoding matrix, the effective channel matrix is $\mathbf{H}_p(k) \triangleq \mathbf{H}(k)\mathbf{W}_{M_t,n(k)}$ so that the $N_r \times 1$ received signal vector $\mathbf{y}(k)$ for the $k^{th}$ subcarrier can be written as

$$\mathbf{y}(k) = \mathbf{H}_p(k)\sqrt{\mathbf{A}(k)}\mathbf{x}(k) + \mathbf{v}(k),$$

where $\mathbf{x}(k)$ is an $M_t \times 1$ transmit signal vector. The constellation size is normalized such that $E[\mathbf{x}(k)\mathbf{x}^H(k)] = \mathbf{I}_{M_t}$. $\mathbf{v}(k)$ is the $N_r \times 1$ zero-mean complex Gaussian noise vector with variance $N_0$ for the $k^{th}$ subcarrier with elements $v(k)$ that are independent, and identically distributed (i.i.d.). Note that $\mathbf{v}(k)$ is independently generated for every subcarrier. $\mathbf{A}(k)$ is an $M_t \times M_t$ diagonal power allocation matrix, where $[\mathbf{A}(k)]_{ii}$ denotes the average symbol energy at the $i^{th}$ transmit antenna for the $k^{th}$ subcarrier for the duration of one OFDM symbol. This will be elaborated further in the next section as part of the precoder design. The estimated signal $\widehat{\mathbf{x}}(k)$ at the receiver can be written as

$$\widehat{\mathbf{x}}(k) = \mathbf{G}_p(k)\mathbf{y}(k) = \sqrt{\mathbf{A}(k)}\mathbf{x}(k) + \mathbf{H}_p^\dagger(k)\mathbf{v}(k), \quad (1)$$

where $\mathbf{G}_p(k)$ denotes the equalization matrix. In the case of ZF equalizer (ZFE), $\mathbf{G}_p(k) = \mathbf{H}_p^\dagger(k)$.

## 3. PROPOSED UNIMODE PRECODING SCHEME

In the present scheme, the precoding matrix $\mathbf{W}_{M_t,n(k)}$ is designed to minimize the average error probability under a constant rate constraint. Specifically, the optimal values of $n(k)$, denoted as $n^*(k)$ henceforth, are determined at the receiver and sent back to the transmitter as precoding parameters via the feedback channel. The bitstream at the transmitter is converted to multiple data streams by the spatial-frequency multiplexer (SF-Mux). All the data streams are mapped to transmit antennas according to the precoding parameters and transmitted over the wireless channel after OFDM modulation. At the receiver, the received signal will be equalized with per-tone ZFEs corresponding to the antenna selection at the transmitter. The equalized data streams will then pass through the symbol detector and convert to bitstream with the spatial-frequency demultiplexer (SF-Demux).

For $M$-QAM constellation with Gray coding employed for all the data streams, the BER expression of the $i^{th}$ data stream for the $k^{th}$ subcarrier can be approximated as [17]

$$\begin{aligned} P_{b_i}\left(\mathbf{W}_{M_t,n(k)}\right) &\approx \frac{\sqrt{M-1}}{\sqrt{M}\log_2\sqrt{M}}\operatorname{erfc}\left(\sqrt{\mathrm{SNR}_i(k)\frac{3\eta}{2(M-1)}}\right) \\ &= \frac{\sqrt{M}-1}{\sqrt{M}\log_2\sqrt{M}} \\ &\quad \times \operatorname{erfc}\left(\sqrt{\frac{[\mathbf{A}(k)]_{ii}}{N_0\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii}}\frac{3\eta}{2(M-1)}}\right), \end{aligned} \quad (2)$$

where $\operatorname{erfc}(\cdot)$ is the complementary error function and $\mathrm{SNR}_i(k)$ denotes the (post-processing) SNR of the $i^{th}$ data stream for the $k^{th}$ subcarrier at the output of the ZFE, which can be obtained from (1). The post-processing SNR is the parameter of interest in (2) because the channel noise is colored by the ZFE, and thus, the noise power can vary as a function of the channel [16]. Therefore, the average BER

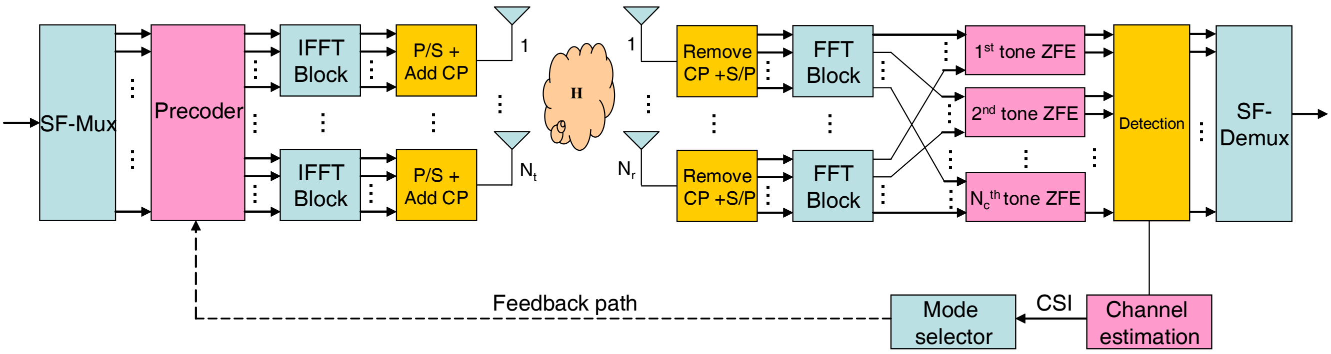


Fig. 1. Block diagram of proposed unimode precoding scheme.

expression for MIMO-OFDM based systems with precoding and linear equalization is written as

$$\overline{P}_b\left(\overline{\mathbf{W}}\right) = \frac{1}{\alpha}\sum_{k=1}^{N_c}\sum_{i=1}^{M_t} P_{b_i}\left(\mathbf{W}_{M_t,n(k)}\right) = \frac{\sqrt{M}-1}{\alpha\sqrt{M}\log_2\sqrt{M}}\sum_{k=1}^{N_c}$$
$$\sum_{i=1}^{M_t}\operatorname{erfc}\left(\sqrt{\frac{[\mathbf{A}(k)]_{ii}}{N_0\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii}}\frac{3\eta}{2(M-1)}}\right), \tag{3}$$

where

$$\overline{\mathbf{W}} = \left[\begin{array}{cccc}\mathbf{W}_{M_t,n(1)} & \mathbf{W}_{M_t,n(2)} & \cdots & \mathbf{W}_{M_t,n(N_c)}\end{array}\right],$$

which contains all the precoding matrices specified for the corresponding subcarriers, and $\alpha \triangleq N_c M_t$ denotes the total number of data streams at the transmitter. In addition, the total transmission rate for the unimode scheme is

$$b_T = \alpha\log_2(M) = N_c M_t \log_2(M), \tag{4}$$

which is used as the rate constraint in the proposed formulation.

From (3), it is clear the elements of the power allocation matrix $[\mathbf{A}(k)]_{ii}$ play a significant role in determining the BER. An obvious choice is to use equal power allocation so that $[\mathbf{A}(k)]_{ii} = E_b\log_2(M)$, where $E_b$ denotes the energy per transmitted bit. From (3), the average BER for unimode precoding can then be written as

$$\begin{aligned}\overline{P}_{b,\mathrm{UMEP}}\left(\overline{\mathbf{W}}\right) &= \frac{1}{N_c M_t}\sum_{k=1}^{N_c}\sum_{i=1}^{M_t} P_{b_i}\left(\mathbf{W}_{M_t,n(k)}\right)\\ &= \frac{1}{N_c}\sum_{k=1}^{N_c} P_{b_{\mathrm{avg}}}\left(\mathbf{W}_{M_t,n(k)}\right),\end{aligned} \tag{5}$$

where $P_{b_{\mathrm{avg}}}\left(\mathbf{W}_{M_t,n(k)}\right) \triangleq \frac{1}{M_t}\sum_{i=1}^{M_t} P_{b_i}\left(\mathbf{W}_{M_t,n(k)}\right)$ is the average BER for the $k^{th}$ subcarrier. Obviously, to minimize $\overline{P}_{b,\mathrm{UMEP}}(\overline{\mathbf{W}})$ is equivalent to minimizing $P_{b_{\mathrm{avg}}}(\mathbf{W}_{M_t,n(k)})$ for each subcarrier. From (2), the average BER for the $k^{th}$ subcarrier using equal power allocation can be written as

$$P_{b_{\mathrm{avg}}}^{(\mathrm{UMEP})}\left(\mathbf{W}_{M_t,n(k)}\right) = \frac{\sqrt{M}-1}{M_t\sqrt{M}\log_2\sqrt{M}}$$
$$\sum_{i=1}^{M_t}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii}}\frac{3\eta\log_2 M}{2(M-1)}}\right),$$

and the BER optimized unimode equal power (UMEP) precoder for each subcarrier is

$$\mathbf{W}_{M_t,n^*(k)}^{(\mathrm{UMEP})} = \underset{\mathbf{W}_{M_t,n(k)}\in\mathscr{W}_{M_t}}{\arg\min}\; P_{b_{\mathrm{avg}}}^{(\mathrm{UMEP})}\left(\mathbf{W}_{M_t,n(k)}\right). \tag{6}$$

To further enhance BER performance, the low complexity inverse power allocation scheme in [18] is also considered. The amount of power allocated in this scheme is inversely proportional to the channel gains such that selected attenuated subcarriers are compensated, thereby boosting BER performance. In other words, $[\mathbf{A}(k)]_{ii}$ is proportional to $\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii}$ such that the post-processing SNR of all the data streams for all subcarriers are equalized. Consequently,

$$[\mathbf{A}(k)]_{ii} = \frac{\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii} E_b b_T}{\sum_{k=1}^{N_c}\sum_{i=1}^{M_t(k)}\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii}}, \tag{7}$$

where $E_b b_T$ denotes the total transmitted power. Substituting (7) into (3), the average BER using inverse power allocation can be written as

$$\overline{P}_{b,\mathrm{UMIP}}(\overline{\mathbf{W}}) = \frac{\sqrt{M}-1}{\sqrt{M}\log_2\sqrt{M}}$$
$$\operatorname{erfc}\left(\sqrt{\frac{E_b b_T}{N_0\sum_{k=1}^{N_c}\sum_{i=1}^{M_t}\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii}}\frac{3\eta}{2(M-1)}}\right).$$

It is obvious that minimizing $\overline{P}_{b,\mathrm{UMIP}}(\overline{\mathbf{W}})$ is equivalent to minimizing $\sum_{k=1}^{N_c}\sum_{i=1}^{M_t}\left[\left(\mathbf{H}_p^H(k)\mathbf{H}_p(k)\right)^{-1}\right]_{ii}$ for each subcarrier. Hence, the BER optimized unimode inverse power (UMIP) precoder for each subcarrier is

$$\mathbf{W}_{M_t,n^*(k)}^{(\mathrm{UMIP})} = \underset{\mathbf{W}_{M_t,n(k)}\in\mathscr{W}_{M_t}}{\arg\min}\sum_{i=1}^{M_t}\sigma_i^{-2}\left(\mathbf{H}_p(k)\right). \tag{8}$$

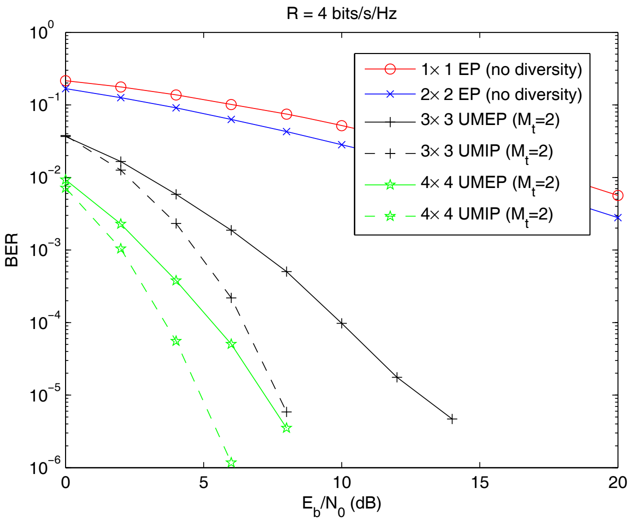


Fig. 2. BER vs. SNR performance for unimode schemes ($R = 4$ bits/s/Hz).

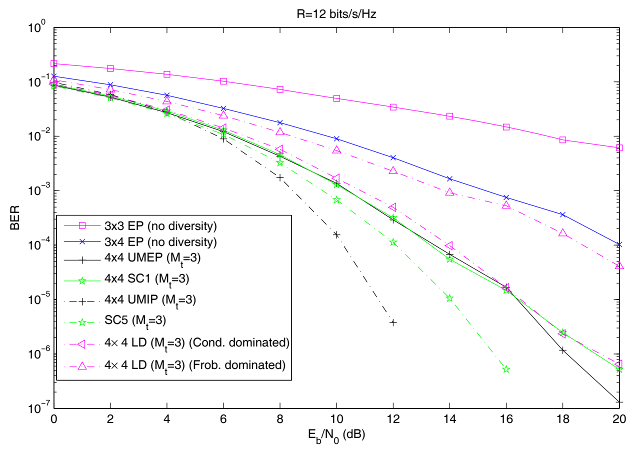


Fig. 3. BER vs. SNR performance between unimode, SC1 [14], SC5 [15] and LD [8] schemes ($R = 12$ bits/s/Hz).

## 4. SIMULATION RESULTS

In all simulations, $N_c = 64$ and $N_{cp} = 16$. In this case, $\eta = 0.8$. The channel coefficients are directly generated independently in the frequency domain with a Rayleigh distribution, where the fading process is normalized such that $E\left[|H_{i,j}(k)|^2\right] = 1$. The channels were held static during one OFDM symbol.

The BER performance for the UMEP and UMIP precoding schemes are shown in Figure 2 with spectral efficiency $R = M_t \log_2(M) = 4$ bits/s/Hz and $M_t = 2$. The constellation is chosen such that the transmission rate constraint $b_T$ is satisfied. In the following, $X \times Y$ denotes MIMO-OFDM based spatial multiplexing systems with $X$ transmit and $Y$ receive antennas. $3 \times 3$, and $4 \times 4$ systems are considered. In addition, $1 \times 1$ and $2 \times 2$ systems with no precoding (no diversity) are also plotted for comparison. In this instance, equal power (EP) allocation is used. From Figure 2, the proposed unimode precoding schemes can achieve lower BER than $1 \times 1$ and $2 \times 2$ systems as they do not benefit from any selection diversity. Note that the performance gap in the $4 \times 4$ system between the UMEP and UMIP algorithms is less than that of the $3 \times 3$ system. This is because the extra antenna pair increases the spatial diversity, hence, the proposed unimode schemes can directly benefit from extra selection diversity to select antenna subset of good quality without exploiting the diversity over all the subcarriers.

The BER performances for various precoding schemes in a $4 \times 4$ system with spectral efficiency $R = M_t \log_2(M) = 12$ bits/s/Hz and $M_t = 3$ are shown in Figure 3. In addition to the unimode schemes, SC1 scheme in [14] and the SC5 in [15] are also included. Since SC1 and SC5 were originally proposed for MIMO spatial multiplexing systems, a MIMO-OFDM implementation of the two schemes are used here. SC1 is an unimode scheme where an optimal antenna subset is selected based on the maximum minimum post-processing SNR. SC5 is a multimode scheme in which the optimal modes for $M_t$ and $M$-QAM pair are chosen. In the simulation, $M = 16$ is used to achieve 12 bits/s/Hz spectrum efficiency for each subcarrier. The MIMO-OFDM precoding scheme proposed in [8] is also included. Even though the scheme proposed in [8] is designed for MIMO-OFDM systems, the selection criterion is simply based on selection of the antenna subset for each subcarrier that can provide the maximum Frobenius norm as well as the minimum condition number of the effective channel matrix. It is claimed that if the two criteria (maximum Frobenius norm and the minimum conditional number) are not mutually satisfied for any effective channel matrices for a particular subcarrier, nothing will be transmitted on the corresponding subcarrier. If this is the case, this will imply the scheme proposed in [8] is a non-constant rate transmission system. In order to make a fair comparison with the proposed unimode schemes, a modified version of [8] is used. If the two criteria (maximum Frobenius norm and the minimum condition number) are both satisfied, the antenna subset is chosen according to [8], otherwise, the antenna subset for the corresponding subcarrier is chosen either by minimum condition number (labeled as “Cond. dominated”) or maximum Frobenius norm (labeled as “Frob. dominated”). From the figure, the proposed UMEP algorithm performs similarly to the SC1 scheme, outperforms the scheme in [8], and underperforms the SC5 scheme. This is because the SC5 scheme exploits adaptive modulation to enhance BER performance. The UMIP precoding scheme, however, outperforms SC5 because it exploits the extra diversity offered by the weak subcarriers. This shows that BER performance can be improved by exploiting channel gain diversity in frequency-selective fading channels. However, this performance gain comes at the cost of extra feedback information from the receiver as the amount of power allocated for each data stream needs to be transmitted. Therefore, the performance of inverse power allocation based precoder is expected to be more sensitive to inaccuracy or delay in the CSI feedback.

## 5. CONCLUSION

A unimode antenna selection/precoding algorithm has been proposed for MIMO-OFDM based spatial muxltiplexing systems. Simulation results show that the proposed schemes can exploit the spatial diversity as well as channel gain diversity to enhance the link reliability. Furthermore, the inverse power allocation strategy simplifies the precoder design compared to that of the equal power since only the eigenmodes of the effective channel matrix are used.

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