

Adaptive Precoding for Switching between Spatial Multiplexing and Diversity in MIMO OFDM with Transmit Antenna and Path Correlations

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Abstract—The path and antenna correlations significantly degrade the system capacity in spatially-multiplexed multiple-input multiple-output (MIMO) orthogonal frequency-division multiplexing (OFDM) systems and increase bit error rate (BER) in orthogonal space-time block coded (OSTBC) OFDM. We develop adaptive dual-mode precoding to improve system performance with transmit antenna and path correlations. Both linear and non-linear Tomlinson-Harashima (TH) precoders are considered. In our proposed approach, precoding for maximizing capacity in spatially-multiplexed OFDM or precoding for minimizing error rate in OSTBC OFDM, is adaptively chosen at the receiver, and only one-bit decision information per subcarrier needs to be sent back to the transmitter. The precoding mode selection depends on the channel conditions. To determine the precoding matrix only the statistical knowledge of the channel is needed at the transmitter, which significantly reduces the feedback requirements. In spatially correlated channels, proposed adaptive dual-mode precoding individually outperforms either capacity-maximization precoding in spatially-multiplexed OFDM or error-rate-minimization precoding in OSTBC OFDM.

Index Terms—linear precoding, THP, MIMO, OSTBC, spatial multiplexing, OFDM

I. INTRODUCTION

The multiple-input multiple-output (MIMO) technique, including the use of arrays of transmit and receive antennas, improves capacity, quality, and reliability of wireless transmission. It takes advantage of the spatial diversity created by spatially uncorrelated antennas in a dense multipath scattering environment. MIMO systems can be implemented either with spatial multiplexing techniques to achieve high capacity or with space-time diversity codes to maximize diversity gain. Orthogonal space-time block coding (OSTBC)¹ [1], [2] is an important coding technique to exploit the total available spatial diversity in MIMO channels with low decoding complexity, and has been widely used. For a high-data-rate transmission, the multipath environment is usually frequency selective. Orthogonal frequency-division multiplexing (OFDM) converts such frequency-selective channel into a set of parallel frequency-flat subchannels, therefore reducing the receiver's complexity. Since spatial multiplexing techniques and OSTBC can be readily implemented on OFDM subcarrier basis, full

capacity or full diversity can be achieved in MIMO OFDM on independent identically distributed (i.i.d.) Rayleigh channels.

In a practical system, however, antenna and/or path correlations may exist. Transmit antennas can be correlated if the distance between adjacent antennas is not sufficient. The propagation paths may also be correlated since there can be scatterers far from the transmit antenna array in a narrow angular range, which may cause multipath signals that bounce off these scatterers to be temporally correlated (correlated scattering). Spatial correlations significantly reduce the system capacity [3] and increase the system bit error rate (BER) [4]. With only channel correlation matrices at the transmitter, precoding can mitigate capacity loss in spatially-multiplexed (SM) MIMO systems [5] or improve BER for OSTBC systems in spatially correlated flat-fading MIMO channels [6], [7]. For OFDM in antenna and path-correlated frequency-selective channels, precoding enables pre-processing of the signals at a subcarrier level and improves capacity in spatially-multiplexed OFDM [8] or BER in OSTBC OFDM [9]. Nevertheless, effective precoding for spatially-multiplexed OFDM and OSTBC OFDM has not been investigated in antenna and path-correlated channels.

In this paper, we are investigating MIMO systems that dynamically switch between spatial multiplexing and space-time coding. The fundamental diversity-multiplexing trade-off in the high SNR region has been analyzed in [10], and non-asymptotic results have been given in [11]. For practical system design low-error-rate and high-data-rate techniques may be desired. A switching algorithm between spatial multiplexing and diversity is proposed in [12]. [13] presents an antenna selection scheme to choose transmit antennas for spatial multiplexing or selection diversity mode. A multi-mode linear precoder with limited feedback is proposed in [14]. These approaches [12]–[14] employ selection diversity combining to improve error rates in high data-rate transmission. However, only uncorrelated flat-fading MIMO channels have been considered there.

In this paper, we develop adaptive dual-mode precoders for MIMO OFDM in the presence of transmit antenna and path correlations; both linear precoding and non-linear Tomlinson-Harashima precoding (THP) are considered. Our major purpose is to design precoding which leads to low error rates

¹OSTBC here stands for orthogonal space-time block-coded and orthogonal space-time block coding, depending on the context.

without reducing the transmission data rate. In our precoder, the precoding mode designed for spatially-multiplexed OFDM or OSTBC OFDM is chosen based on the channel conditions to improve error rates. We assume that the perfect channel state information (CSI) is available at the receiver, and the maximum-likelihood (ML) detection is used for both spatially-multiplexed and diversity precoding modes. Thus, the conditional error probability given a channel condition is primarily determined by the distance properties of the codebook (or constellation) at the receiver. The minimum Euclidean distance found by minimizing the difference over all possible codewords, which determines the probability of error, is calculated at the receiver as the precoding selection metric and is employed to derive the switching criterion. A one-bit information of selection decision is sent to the transmitter via a feedback link. At the transmitter, our precoders only need to know the long-term correlation properties rather than instantaneous channel information, which significantly reduces the feedback requirement. In our systems, the constellation size for SM OFDM and OSTBC OFDM is different, such that our adaptive precoding does not reduce the desired transmission rate. The proposed precoder offers the choice between precoding for spatial multiplexing and precoding for diversity according to instantaneous information of antenna and path-correlated MIMO OFDM channels. Our adaptive precoding individually outperforms either capacity-improving precoding in correlated spatially-multiplexed OFDM or BER-improving precoding in correlated OSTBC OFDM in terms of the system BER performance.

II. SYSTEM MODEL

This section will introduce the system model of an N -subcarrier OFDM system with M_T transmit antennas and M_R receive antennas in the presence of transmit antenna and path correlations. We focus on the downlink case, where spatial correlations exist between the transmit antennas, while receive antennas are uncorrelated.

A. Path and Transmit Antenna Correlations

Between the u -th transmit antenna and v -th receive antenna, a wideband frequency-selective fading channel with L resolvable paths is assumed. The l -th path gain is a zero-mean complex Gaussian random variable (Rayleigh fading) with variance σ_l^2 , which can be represented by an $M_R \times M_T$ matrix $\mathbf{h}(l)$ with entries $h_{u,v}(l)$, $\forall l$. We assume that the channel gains remain constant over several OFDM symbol intervals. As in [8], the tap gain vector therefore can be expressed as

$$[\mathbf{h}(0) \cdots \mathbf{h}(L-1)] = \mathbf{h}_w [\mathbf{R}_P^T \otimes \mathbf{R}_T]^{1/2} = \mathbf{h}_w [\mathbf{r}_P^T \otimes \mathbf{r}_T], \quad (1)$$

where \mathbf{h}_w is an $M_R \times M_T L$ matrix of i.i.d zero mean complex Gaussian random variables with unit variance; $\mathbf{r}_P = \mathbf{R}_P^{1/2}$ and $\mathbf{r}_T = \mathbf{R}_T^{1/2}$. \mathbf{R}_P is the $L \times L$ path correlation matrix with the $\{m, n\}$ th entry

$$R_P(m, n) = \sigma_m \sigma_n p^{|m-n|} e^{j\theta_{m,n}}, \quad 0 < p \leq 1 \quad (2)$$

where p is the path-correlation factor and $\theta_{m,n}$ is the phase of the path correlation between the m -th and the n -th path. If the paths between each transmit-receive antenna pair are

uncorrelated, i.e., $p = 0$, $\mathbf{R}_P = \text{diag}[\sigma_0^2 \cdots \sigma_{L-1}^2]$ is only determined by the power delay profiles. \mathbf{R}_T is the transmit antenna correlation matrix. From [3], the entries of \mathbf{R}_T are

$$R_T(m, n) = \mathcal{J}_0(2\pi|m-n|\zeta_T), \quad (3)$$

where \mathcal{J}_0 is zero-order Bessel function of the first kind; $\zeta_T = \Delta \frac{d_T}{\lambda_c}$; $\lambda_c = c/f_c$ is the wavelength of at the center frequency f_c , Δ is the angle of arrival spread, and the transmit antennas are spaced by d_T .

B. Antenna and Path Correlations in OFDM

At the receiver, the $M_R \times M_T$ channel matrix on the k -th subcarrier can be represented as

$$\mathbf{H}[k] = \sum_{l=0}^{L-1} \mathbf{h}(l) e^{-j\frac{2\pi}{N} k l}. \quad (4)$$

The l -th path gain matrix $\mathbf{h}(l)$ in (1) and substituting in (4) can be written as

$$\mathbf{H}[k] = \mathbf{h}_w (\mathbf{r}_P^T \mathbf{F}[k] \otimes \mathbf{r}_T) = \mathbf{h}_w \mathbf{r}[k], \quad (5)$$

where $\mathbf{F}[k] = [e^{-j\frac{2\pi}{N} k 0} \cdots e^{-j\frac{2\pi}{N} k(L-1)}]^T$ is an L -dimensional vector; $\mathbf{r}[k] = \mathbf{r}_P^T \mathbf{F}[k] \otimes \mathbf{r}_T$ is an $M_T L \times M_T$ matrix. The k -th received signal vector thus can be given by

$$\mathbf{Y}[k] = \mathbf{H}[k] \mathbf{X}[k] + \mathbf{W}[k], \quad (6)$$

where $\mathbf{Y}[k]$ is an M_R -dimensional vector and $\mathbf{W}[k]$ is the noise vector with the entries $W_v[k] = \sum_{u=1}^{M_T} W_{u,v}[k]$ being additive white Gaussian noise (AWGN) samples with zero mean and variance σ_W^2 , and $W_{u,v}[k]$, $\forall k$, are assumed i.i.d.. The input data vector is $\mathbf{X}[k] = [X_1[k] \cdots X_{M_T}[k]]^T$; $X_u[k]$ denotes an M -ary quadrature amplitude modulation (QAM) symbol on the k -th subcarrier sent by the u -th transmit antenna.

In spatially-multiplexed OFDM, we transmit M_T independent data symbols at each time slot on the k -th subcarrier. The transmission rate is defined as P/T , where P represents the number of symbols transmitted over the T time slots. Thus the transmission rate in the case of spatially-multiplexed OFDM is $R_{SM} = M_T$.

C. OSTBC OFDM

In contrast to spatial multiplexing, space-time diversity coding sends dependent data streams from each transmit antenna. The transmitted data are mapped to a space-time MIMO encoder that assigns the code symbols onto the transmit antennas. At the receiver, the arriving signals are combined such that high diversity order is obtained. STBC based on orthogonal design obtains full diversity gain with low decoding complexity, therefore it is widely used. The $T \times M_T$ code matrix for OSTBC satisfies

$$\mathbf{C}^H \mathbf{C} = \left(\sum_{t=1}^P |c_t|^2 \right) \mathbf{I}_{M_T}, \quad (7)$$

for all complex codewords c_t . The full-rate codes transmit an average of one symbol per symbol period, and hence $R_{ST} = 1$. OSTBC can be directly applied to OFDM at a subcarrier level

to offer full spatial diversity gain, if there is no correlation between transmit antennas or different paths. For example, in full-rate Alamouti-coded OFDM $\begin{pmatrix} X_1[k] & -X_2^*[k] \\ X_2[k] & X_1^*[k] \end{pmatrix}$ is transmitted on subcarrier k , i.e., $X_1[k]$ and $X_2[k]$ are transmitted over the 1-st and 2-nd antenna at the first time slot, respectively; the $-X_2^*[k]$ and $X_1^*[k]$ are transmitted in the following slots. Full-rate complex orthogonal designs do not exist for more than two transmit antennas. The transmission rate of spatial diversity with OSTBC is thus less or equal to 1, i.e., $R_{ST} \leq 1$.

In the presence of transmit antenna and path correlations, direct application of OSTBC in OFDM result in higher system BER, compared with OSTBC OFDM in uncorrelated channels. The correlation also reduces the achievable spectral efficiency (in bits/sec/Hz) of OFDM in frequency-selective fading channels. If the correlation matrices are available at the transmitter, precoding can be applied to mitigate the problem.

III. OPTIMAL PRECODING FOR OFDM IN ANTENNA AND PATH-CORRELATED CHANNELS

In this section, we briefly review linear precoding proposed in [8], which improves the capacity in SM OFDM and linear/non-linear precoding in [9], which minimizes the system error rate in OSTBC OFDM. Precoding in [8] and [9] only requires the information of antenna and path correlations at the transmitter.

A. Linear Precoding in Spatially-Multiplexed OFDM

For SM OFDM, we consider the $M_T \times M_T$ precoding matrix $\mathbf{E}_{SM}[k]$ given in [8]. The suboptimal solution is given by [8]:

$$\mathbf{E}_{SM}[k] = \arg \max \frac{1}{N} \sum_{k=0}^{N-1} \log \det \left(\frac{\eta_k M_R}{M_T} \mathbf{\Gamma}_T \tilde{\mathbf{Z}}_{SM}[k] \mathbf{\Gamma}_T + \mathbf{I}_{M_T} \right), \quad (8)$$

where η_k is the effective SNR on the subcarrier k . $\tilde{\mathbf{Z}}_{SM}[k] = \mathbf{V}_T^H \mathbf{Z}_{SM}[k] \mathbf{V}_T$; $\mathbf{Z}_{SM}[k] = \mathbf{E}_{SM}[k] \mathbf{E}_{SM}^H[k]$, and satisfies $\sum_{k=0}^{N-1} \text{tr}(\mathbf{Z}_{SM}[k]) = NM_T$. The \mathbf{V}_T is the right $M_T \times M_T$ matrix of the singular value decomposition (SVD) of \mathbf{r}_T . The $\mathbf{\Gamma}_T$ is singular value matrix of \mathbf{r}_T ; it is an $M_T \times M_T$ diagonal matrix with real, non-negative entries γ_{T_u} , $u = 1, \dots, M_T$, in descending order $\gamma_{T_1} \geq \gamma_{T_2} \geq \dots \geq \gamma_{T_{M_T}} \geq 0$. The suboptimal solution is more practical and efficient since it does not use numerical optimization, while it results in almost the same capacity as the optimal solution [8]. In this paper, we consider the suboptimal-capacity precoding for spatially-multiplexed OFDM.

B. Linear and Non-Linear Precoding for OSTBC OFDM

For OSTBC OFDM, we consider optimal linear precoding and non-linear THP developed to improve error-rate performance [9]. The $M_T \times M_T$ linear precoding matrix can be given by [9]:

$$\mathbf{E}_{ST}[k] = \arg \max_{\text{tr}(\mathbf{Z}[k])=M_T} \log \det \left(\frac{d_{ST_{\min}}}{4\sigma_W^2} \mathbf{R}[k] \mathbf{Z}_{ST}[k] + \mathbf{I}_{M_T} \right), \quad (9)$$

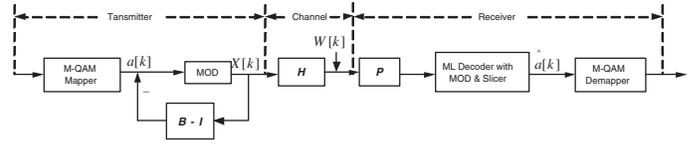


Fig. 1. Tomlinson-Harashima precoding in OSTBC OFDM.

where $\mathbf{Z}_{ST}[k] = \mathbf{E}_{ST}[k] \mathbf{E}_{ST}^H[k]$; $\mathbf{R}[k] = \mathbf{r}^H[k] \mathbf{r}[k]$ and $\mathbf{r}[k]$ is defined in (5). $d_{ST_{\min}}$ is the minimum distance of the transmit constellation used in OSTBC OFDM.

The structure of non-linear THP for OSTBC OFDM in antenna and path-correlated channels proposed in [9] is shown in Fig. 1. THP is an effective pre-processing technique to simplify the receivers' complexity and suppress interference, and has been widely studied [15]–[18]. The scaling matrix \mathbf{P} keeps the average transmit power constant. Regardless of the modulo device, the feedback filter is equivalent to $\mathbf{B}_{ST}[k] = \mathbf{E}_{ST}^{-1}[k]$, which can be optimally designed according to (9). If the input sequence $a[k]$ is a sequence of i.i.d. symbols, the output of the modulo device is also a sequence of i.i.d. random variables, and the real and imaginary parts are independent, i.e., we can assume $\mathbf{E}[\mathbf{X}[k] \mathbf{X}^H[k]] = E_s \mathbf{I}_{M_T}$, $\forall k$ [16]. At the receiver, the effective channel is $\mathbf{H}[k] \mathbf{E}_{ST}[k]$ and ML decoding is used. After the ML decoding and discarding the modulo congruence, the unique estimates of the data symbols can be generated. Similarly, the non-linear precoding can be used for spatially-multiplexed OFDM with $\mathbf{B}_{SM}[k] = \mathbf{E}_{SM}^{-1}[k]$, which can be designed as in (8). Using THP the full capacity of the underlying MIMO channel can be achieved [15]. The details of THP can be found in [16].

Obviously, the precoding matrices in (8) and (9) only need the knowledge of the correlation matrices. The full channel state information at the receiver (CSIR) does not need to be sent to the transmitter, which significantly reduces the feedback requirement. Precoding in [8] and [9] only focuses on either capacity improvement in spatially-multiplexed OFDM or BER improvement in OSTBC OFDM. It is still unclear how to choose spatial-multiplexing-based precoding and diversity-based precoding in OFDM with antenna and path correlations.

IV. ADAPTIVE DUAL-MODE PRECODING

In this section, we propose adaptive precoding which switches between precoding (8) for spatially-multiplexed OFDM and precoding (9) for OSTBC OFDM. The ML decoding is used for both modes. The Euclidean distance of the codebook is calculated at the receiver as selection metric by which the receiver adaptively selects the precoding mode between spatial multiplexing and diversity, and sends the one-bit decision information back to the transmitter. The system maintains a fixed total rate of R bits/s/Hz per space-time symbol. Perfect CSI is assumed available at the receiver and only the correlation information is available at the transmitter.

With a precoding matrix $\mathbf{E}[k]$ at the transmitter, the transmitted data vector is $\mathbf{E}[k] \mathbf{X}[k]$ instead of $\mathbf{X}[k]$, and the effective channel is $\mathbf{H}_{\text{eff}}[k] = \mathbf{H}[k] \mathbf{E}[k]$. After reception the receiver performs ML decoding on the subcarrier basis in spatially-multiplexed or OSTBC OFDM. The performance of

spatially-multiplexed OFDM or OSTBC OFDM with an ML receiver depends on the effective channel and the minimum Euclidean distance of the received codebook, $d_{\min}(\mathbf{H}_{\text{eff}}[k])$. Similarly as in [12], given the total rate R , union bound to upperbound the conditional error probability can be given by

$$\Pr(\text{error}|\mathbf{H}_{\text{eff}}[k]) \leq (2^R - 1) Q\left(\sqrt{\frac{E_s}{4\sigma_W^2}} d_{\min}^2(\mathbf{H}_{\text{eff}}[k])\right), \quad (10)$$

where $Q(\cdot)$ is the Gaussian Q-function. To keep the overall rate R fixed, the transmitted symbols on each subcarrier in SM OFDM are yielded from a constellation with R/M_T bits per symbol, while those in OSTBC OFDM are generated from a constellation with R bits per symbol if full-rate diversity coding is used. The minimum Euclidean distance of the received codebook determines the performance as a function of the effective channel matrix. Hence, it is chosen as a metric for comparison between different precoding modes. The metric is calculated at the receiver and only one-bit selection decision is fed back.

A. Spatially-Multiplexed OFDM

Since the codewords undergo a transformation by the channel, which does not preserve their distance properties, the minimum Euclidean distance of the received codebook cannot be readily obtained. However, we can derive a relationship between the received codebook and the transmit constellation, similarly as in [12]. In this subsection, we give a lower bound on the minimum distance of the received codebooks for spatially-multiplexed transmission.

The minimum Euclidean distance of the received codebook, d_{SM} , can be found by minimizing the difference over all possible transmitted signal vectors, which is

$$\min \|\mathbf{X}[k] - \mathbf{X}'[k]\|^2 = \frac{d_{\min, \text{sm}}^2}{M_T}, \quad (11)$$

where $d_{\min, \text{sm}}$ is the minimum distance of the transmit constellation used in a spatially-multiplexed transmission. Similarly as in [12], the minimum Euclidean distance of the received codebook can be upper and lower bounded as

$$\gamma_{\min}^2(\mathbf{H}_{\text{eff}}[k]) \frac{d_{\min, \text{sm}}^2}{M_T} \leq d_{\text{SM}}^2 \leq \gamma_{\max}^2(\mathbf{H}_{\text{eff}}[k]) \frac{d_{\min, \text{sm}}^2}{M_T}, \quad (12)$$

where $\{\gamma_i(\mathbf{G})\}$ is the real, non-negative singular value of the matrix \mathbf{G} in descending order. We get the equalities on both sides if and only if the effective channel is unitary. Since the lower bound in (12) gives us the worst case in precoded spatially-multiplexed OFDM, the error rate of spatially-multiplexed OFDM with precoding (8) depends on the minimum singular value γ_{\min} of the effective channel.

B. OSTBC OFDM

For simplicity, we consider the full-rate codes, i.e., $R_{\text{ST}} = 1$. The transmitted data are thus from a constellation with R bits/s/Hz per symbol instead of R/M_T in the multiplexing case. For a $T \times M_T$ full-rate code, the channel needs to stay constant over T OFDM symbols.

For the full-rate STBC code, based on the maximum SNR criterion in [19], we have

$$d_{\text{ST}}^2 \leq \frac{d_{\min, \text{st}}^2}{M_T} \|\mathbf{H}_{\text{eff}}\|_F^2 = \frac{d_{\min, \text{st}}^2}{M_T} \sum_{i=1}^{\mathcal{L}} \gamma_u^2(\mathbf{H}_{\text{eff}}[k]), \quad (13)$$

where $\|\cdot\|_F$ denotes the Frobenius norm; and $\mathcal{L} = \min(M_R, M_T)$ is the rank of the effective channel. The equality (13) holds for Alamouti codes, and gives an upper bound on minimum Euclidean distance [19]. Comparing (12) with (13), we can see that in OSTBC OFDM with precoding (9), the channel impacts the error rate by the sum of singular values of the channel; while the error rate in precoding (8) for SM OFDM is directly determined by the minimum singular value. If we do not want to reduce the desired data rate in adaptive precoding, SM OFDM will use a constellation with a larger minimum distance although it is more sensitive to the rank of the effective channel. Therefore, the choice between precoding (8) and (9) depends on the channel, constellation and the desired rate.

C. Adaptive Dual-Mode Selection Criterion

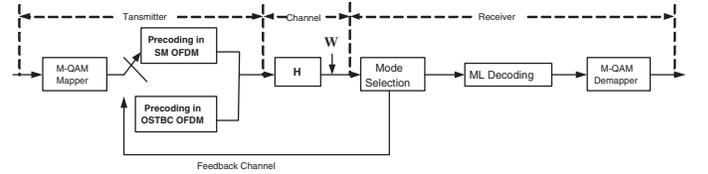


Fig. 2. The adaptive dual-mode precoder.

From (12) and (13), we can find a channel condition for which precoding (8) is always better than precoding (9), i.e., the worst case of (8) in spatially-multiplexed OFDM is better than the best case of (9) in OSTBC OFDM. Therefore, the precoding mode (8) is selected when

$$\frac{d_{\text{STmin}}^2}{M_T} \|\mathbf{H}_{\text{eff}}[k]\|_F^2 \leq \gamma_{\min}^2(\mathbf{H}_{\text{eff}}[k]) \frac{d_{\text{SMmin}}^2}{M_T}, \quad (14)$$

or $\varsigma = \frac{\|\mathbf{H}_{\text{eff}}[k]\|_F}{\gamma_{\min}(\mathbf{H}_{\text{eff}}[k])} \leq \frac{d_{\text{SMmin}}}{d_{\text{STmin}}}$,

This selection criterion makes the receiver choose the precoding mode to exploit the channel condition. When $\varsigma \leq \frac{d_{\text{SMmin}}}{d_{\text{STmin}}}$, (8) is selected, and spatially-multiplexed OFDM is used for transmission; otherwise, OSTBC OFDM is applied. The decision is then transferred to the transmitter by a one-bit information.

The basic structure of the proposed system is shown in Fig. 2. The transmitter contains a switch between precoding mode (8) in spatially-multiplexed OFDM and (9) in OSTBC OFDM. The receiver contains the corresponding ML receiver, and a mode selection unit using a low-bandwidth feedback link. If non-linear precoding is included in either spatially-multiplexed or OSTBC OFDM, the modulo arithmetic feedback structure in Fig. 1 is applied to the corresponding precoding unit in Fig. 2; the receiver structure changes accordingly.

Our precoding adapts OFDM systems to the instantaneous channel conditions. Since the desired transmission rate is

constant, at a certain SNR point, we have the same multiplexing gain for both spatially-multiplexed OFDM and OSTBC OFDM. (Note that here we use the non-asymptotic definition of the multiplexing gain as in [11].) However, there may exist channel realizations where spatial multiplexing has a lower error rate than OSTBC. The measurement ς indicates when (8) in SM OFDM offers better performance and vice versa. Our precoding thus can adaptively choose the precoding mode which offers lower error rates for an OFDM link in antenna and path-correlated MIMO channels, without reducing the system data rate.

V. SIMULATION RESULTS

We show how the new adaptive precoding improves the BER performance for OFDM in antenna and path-correlated frequency-selective MIMO environments. The vehicular B channel specified by ITU-R M. 1225 [20] is used, in which the channel tap gains are zero-mean complex Gaussian random processes with variances of -4.9 dB, -2.4 dB, -15.2 dB, -12.4 dB, -27.6 dB, and -18.4 dB relative to the total power gain. Perfect CSI is assumed available at the receiver and ML decoding is used. The transmitter only knows information of the correlation matrices \mathbf{R}_T and \mathbf{R}_P with $\zeta_T = \Delta \frac{d_T}{\lambda}$ and path-correlation factor p , respectively; the phase of the path correlation $\theta_{m,n}$ in (2) is zero. The angle of arrival spread is assumed 12° , i.e., $\Delta \approx 0.2$. For simplicity, the Alamouti code with 2 transmit antennas is considered. The desired transmission rate is $R = 4$ bits/s/Hz. With 2 transmit antennas, the adaptive precoding selects between precoding (8) for 4-QAM spatially-multiplexed OFDM and precoding (9) for 16-QAM Alamouti-coded OFDM in antenna and path-correlated channels.

Fig. 3 illustrates the BER of adaptive dual-mode precoding in 2×2 64-subcarrier OFDM with only transmit antenna correlations, $\zeta_T = 0.25$ and $p = 0$. Both linear and non-linear precoders are considered. The BERs of precoding (9) for 16-QAM Alamouti-coded OFDM (Case 1) and precoding (8) for 4-QAM spatially-multiplexed OFDM (Case 2) in spatially-correlated channels are also separately given for reference. The linear and non-linear TH precoders in the both cases do not have the adaptive structure. Obviously, different diversity advantages of spatial-multiplexing and Alamouti coding change the slope of the BER curves at high SNR. The curves of Case 1 and Case 2 cross approximately at the SNR of 13 dB in case of linear precoding, i.e., Case 2 exhibits a lack of diversity gains when SNR is larger than 13 dB. For THP, the curves of Case 1 and Case 2 cross approximately at the SNR of 14 dB. For our adaptive precoding, the better precoding mode is chosen for each channel realization, which introduces selection diversity combining gain. We therefore have almost 1 dB improvement over Case 1 and 3 dB gain over Case 2 in the high SNR region. Non-linear THP outperforms linear precoding.

In Fig. 4, we consider non-linear adaptive precoding for 2×2 and 2×4 OFDM with $\zeta_T = 0.5$ and $p = 0$. Similar conclusions can be drawn as from Fig. 3. The curves of Case 1 and 2 cross at 12 dB. Our adaptive THP offers substantial BER gains over the two cases.

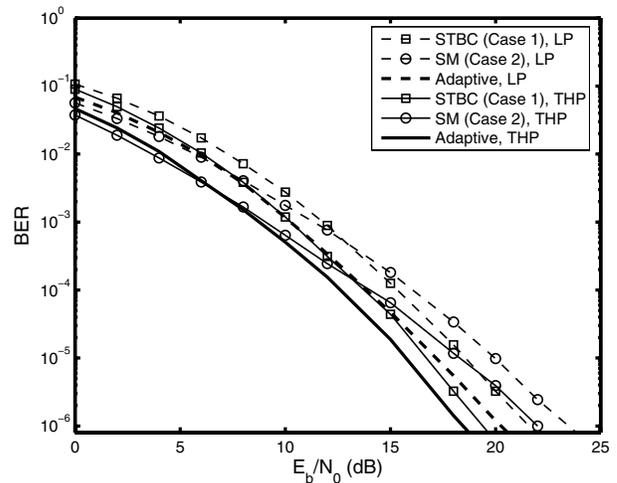


Fig. 3. BER as a function of SNR for linear and non-linear precoding with and without adaptation in 2×2 64-subcarrier OFDM systems with transmit antenna correlations. $R = 4$ bits/s/Hz and $\zeta_T = 0.25$.

The correlation factors $p = 0.9$ and $\zeta_T = 0.25$ are considered in Fig. 5. The proposed linear and non-linear precoders are compared to precoding without adaptation in Case 1 and Case 2. The crossing point for linear and non-linear precoding is 17 dB and 11 dB, respectively. Evidently, linear and non-linear adaptive precoding individually outperform their non-adaptive counterparts in Case 1 and 2. Non-linear adaptive THP outperforms linear adaptive precoding: at $\text{BER} = 10^{-5}$, there is 1.5 dB gain.

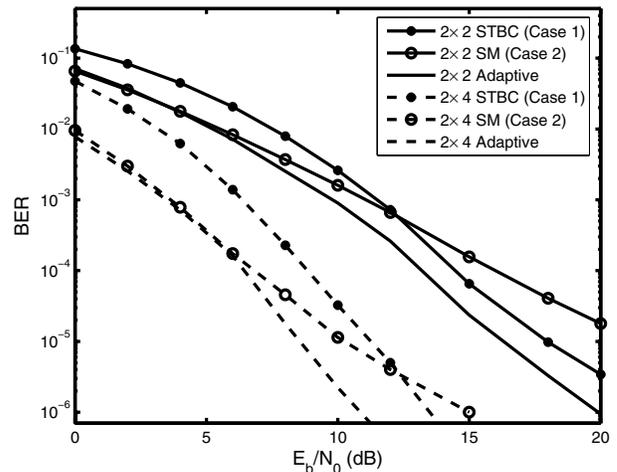


Fig. 4. BER as a function of SNR for THP with and without adaptation in 2×2 and 2×4 64-subcarrier OFDM systems with transmit antenna correlations. $R = 4$ bits/s/Hz and $\zeta_T = 0.5$.

VI. CONCLUSION

We have developed adaptive precoding for OFDM in transmit antenna and propagation path correlated channels to improve the system error-rate performance. Both linear and non-linear TH precoders have been considered. In our proposed

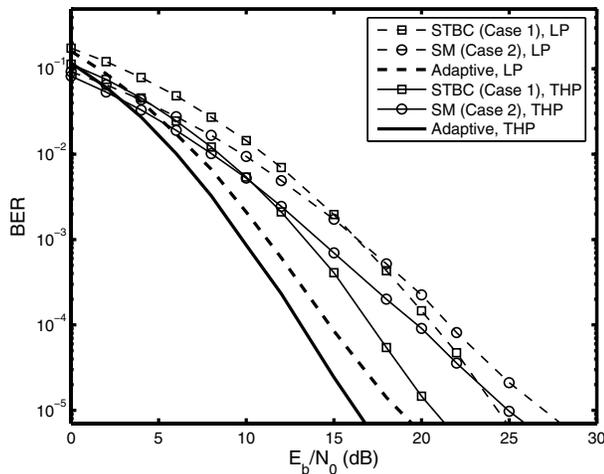


Fig. 5. BER as a function of SNR for linear and non-linear precoding with and without adaptation in 2×2 64-subcarrier OFDM systems with transmit antenna and path correlations. $R = 4$ bits/s/Hz, $\zeta_T = 0.25$ and $p = 0.9$.

approach, spatial-multiplexing-based or diversity-based precoding mode, is adaptively chosen at the receiver according to the channel conditions, and only one-bit information of mode selection needs to be sent back to the transmitter. To design the precoding matrix only the statistical knowledge of the channel is needed at the transmitter, which significantly reduces the feedback requirements. The adaptive dual-mode precoding outperforms optimal precoding individually in either spatially-multiplexed OFDM or OSTBC OFDM in terms of the system BER performance; non-linear adaptive precoding outperforms linear adaptive precoding.

ACKNOWLEDGEMENT

The authors gratefully acknowledge funding for this work provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada, Alberta Informatics Circle of Research Excellence (iCORE), TRILabs, and Rohit Sharma Professorship.

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