

A Study of Insufficient Cyclic Prefix by using Precoding for MIMO-OFDM Systems

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Abstract— In an orthogonal frequency division multiplexing (OFDM) system, the cyclic prefix (CP) is added to the beginning of each symbol to prevent intersymbol interference (ISI) and intercarrier interference (ICI). In practical OFDM system, the CP lengths are fixed. When the CP length is shorter than the channel impulse response (CIR) length, referred to as “insufficient CP”, significant signal distortion can occur at the receiver. This paper proposes the use of precoding technique at the transmitter to solve the ISI and ICI problems owing to insufficient CP. Precoding is first derived for single-input single-output (SISO) OFDM system, and then generalized for multiple input multiple output (MIMO) OFDM system. Simulation results on the bit error rate (BER) versus the signal-to-noise ratio (SNR) demonstrate that the proposed precoding technique is much more efficient the conventional OFDM with one-tap equalization when the CP is insufficient.

Keywords—MIMO-OFDM; precoding; cyclic prefix; channel dependent; insufficient length

I. INTRODUCTION

In future wireless communication system designs are increased spectral efficiency, improved link reliability and achieved data rate. However, wireless communication systems encounter high level of intersymbol interference (ISI) and intercarrier interference (ICI) which originates from multipath propagation and inherent delayed spread [1], [2].

Orthogonal frequency division multiplexing (OFDM) is a multicarrier transmission technique that divides the broadband channel into a number of parallel independent narrowband subchannels by using FFT/IFFT algorithm [1], [2]. A cyclic prefix (CP) is usually added to each OFDM symbol before transmitting it. In order to mitigate ISI and ICI, the CP length must be more than or equal to the channel impulse response (CIR). Otherwise the system suffers from insufficient cyclic prefix distortion is composed of both ISI and ICI [3], [4].

In addition, MIMO systems are promising techniques to increase performance with acceptable bit error rate (BER) by using a number of antennas [4]. The spatial multiplexing transmission technique is used to transmit independent and separately encoded data signals. The antennas at each end transmit independent and separately encoded data signals. The antenna at each ends of the communications circuit is combined to minimize errors and optimizes data speed. If the transmitter has N_t antennas and the receiver has N_r antennas,

the maximum spatial multiplexing order (the number of the stream) is $\min(N_t, N_r)$ [3].

A MIMO-OFDM system transmits OFDM modulated data from multiple antennas at the transmitter. Data transmitted with subcarriers at different antennas are mutually orthogonal. The receiver extracts different data stream from different subcarriers after OFDM demodulation and MIMO decoding [3].

In MIMO-OFDM wireless systems, spatial multiplexing is a common technique used for the antennas to increase the diversity against multipath fading or spatially separate devices [4]. Precoding at the transmitter is a big issue. A considerably long CP is needed if the multipath delay spread is large, resulting in a various loss in both bandwidth and power efficiencies. In order to improve the transmission efficiency, MIMO-OFDM systems with sufficient CP have been studied significantly in the past. In [5], [6] a precoding technique is proposed to eliminate the distortion by processing the information symbols at transmitter side. In MIMO-OFDM systems with sufficient CP, the cyclic prefix has to be as long as the CIR. However, in practical designs, the cyclic prefix is usually fixed. As a result, distortion might occur at the channel output if the channel impulse response is longer than the cyclic prefix. The distortion may be so severe that it dominates other noise. In order to overcome the distortion caused by insufficient CP length. A precoder is used at the transmitter to ensure that distortion does not exist at the receiver. MIMO-OFDM systems with insufficient CP have been studied significantly in the past for example, In [7] a precoding is proposed to eliminate the distortion by processing the information symbols at the transmitter and it also requires the perfect of the channel state information at the transmitter (CSIT). In [8] proposed a channel independent precoding scheme for a MIMO-OFDM system with insufficient CP by using the interference alignment (IA) and singular value decomposition (SVD) method.

In this paper, we propose a channel dependent precoding scheme for a MIMO-OFDM system with insufficient CP by using the precoding technique. We use QPSK modulation schemes and assume that the channel transfer function is known to both the transmitter and receiver sides.

II. SYSTEM MODEL

A. SISO-OFDM Model

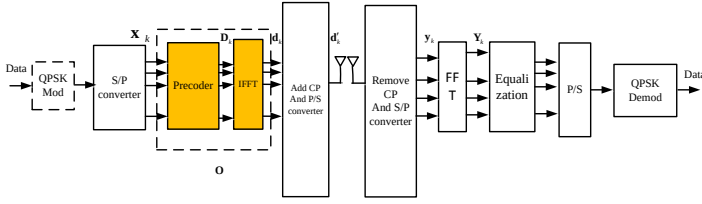


Figure 1 SISO-OFDM System Model.

Consider a SISO-OFDM system with N subcarriers over a frequency selective fading channel and depicts in Figure 1. The data stream is modulated by a QPSK modulation. Let N be the number of subcarriers, $\mathbf{D}_k$ be the QPSK symbols to be transmitted on the subcarrier k , $\mathbf{P}$ and $\mathbf{O}$ be the precoding matrix. Denote the impulse response of the channel by $\mathbf{h} = [h_0, h_1, \dots, h_{L-1}]^T$, where L is the length of the CIR. In this paper, we assume that $L \leq N$. We use $\mathbf{D}_k = [D_k^0, D_k^1, \dots, D_k^{N-1}]^T$ to denote the input signal vector of the k^{th} OFDM symbol. Let $\mathbf{Q}$ be the N -point FFT matrix whose element $q_{lm} = \frac{1}{\sqrt{N}} \exp\left(\frac{-j2\pi lm}{N}\right)$. The IFFT operation is performed at the

transmitter and changes the input signal from frequency domain to time domain. A CP of length G is appended to each time domain vector. Since CP is generally insufficient in this work, we have $G \leq L \leq N$. The transmitted OFDM symbol is thus affected by both ICI and ISI components. After the insufficient CP is removed at the receiver, the time domain expression of the k^{th} symbol, can be written as

$$\mathbf{y}_k = (\mathbf{H} - \mathbf{A})\mathbf{Q}^H \mathbf{D}_k + \mathbf{B}\mathbf{Q}^H \mathbf{D}_{k-1} + \mathbf{w}_k, \quad (1)$$

where $\mathbf{w}_k$ denotes the time domain received noise vector with the complex Gaussian distribution $\mathcal{CN}(0, \sigma^2 \mathbf{I})$. The channel matrix $\mathbf{H}$ is a circular matrix of size $N \times N$, $\mathbf{Q}^H$ is the Hermitian transpose of $\mathbf{Q}$, $\mathbf{A}$ and $\mathbf{B}$ denote the ICI and ISI components of the channel, respectively, where $E = L - G - 1$.

$$\mathbf{A} = \begin{bmatrix} \mathbf{0}_{(E) \times (N-E-G)} & \mathbf{S} & \mathbf{0}_{(E) \times (G)} \\ \mathbf{0}_{(N-E) \times (N-E-G)} & \mathbf{0}_{(N-E) \times (E)} & \mathbf{0}_{(N-E) \times (G)} \end{bmatrix}, \quad (2)$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{0}_{(E) \times (N-E)} & \mathbf{S} \\ \mathbf{0}_{(N-E) \times (N-E)} & \mathbf{0}_{(N-E) \times (E)} \end{bmatrix}, \quad (3)$$

$$\mathbf{S} = \begin{bmatrix} h_{L-1} & \dots & \dots & h_{G+1} \\ 0 & h_{L-1} & \dots & h_{G+2} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & h_{L-1} \end{bmatrix}, \quad (4)$$

$$\text{and } \mathbf{H} = \begin{bmatrix} h_0 & 0 & \dots & 0 & h_{L-1} & h_{L-2} & \dots & h_1 \\ h_1 & h_0 & 0 & \dots & 0 & h_{L-1} & \dots & h_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ h_{L-1} & h_{L-2} & \dots & h_0 & 0 & 0 & \dots & 0 \\ 0 & h_{L-1} & h_{L-2} & \dots & h_0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & h_{L-1} & h_{L-2} & h_{L-3} & \dots & h_0 \end{bmatrix}. \quad (5)$$

At the receiver, the time domain signal $\mathbf{y}_k$ in (1) is transformed into the frequency domain signal $\mathbf{Y}_k$ by the FFT matrix $\mathbf{Q}$ of size N . We have

$$\mathbf{Y}_k = \mathbf{Q}(\mathbf{H} - \mathbf{A})\mathbf{Q}^H \mathbf{D}_k + \mathbf{Q}\mathbf{B}\mathbf{Q}^H \mathbf{D}_{k-1} + \tilde{\mathbf{w}}_k, \quad (6)$$

where $\tilde{\mathbf{w}}_k = \mathbf{Q}\mathbf{w}_k$ and $\tilde{\mathbf{w}}_k$ is also distributed as $\mathcal{CN}(0, \sigma^2 \mathbf{I})$. Since we need to perform a precoding, signal $\mathbf{D}_k$ is the precoded output of $N \times 1$ vector $\mathbf{x}_k$ of tentative information symbol passing through a precoding matrix $\mathbf{P}$ of size $N \times N$ and be presented as,

$$\mathbf{D}_k = \mathbf{P}\mathbf{x}_k. \quad (7)$$

The time domain precoding matrix is defined as $\mathbf{O} = \mathbf{Q}^H \mathbf{P}$. After the design of matrix $\mathbf{O}$, the precoding matrix $\mathbf{P}$ can be obtained by multiplying with the inverse $\mathbf{Q}$. Thus, $\mathbf{P}$ and $\mathbf{O}$ are equivalent and in what follows, we call both $\mathbf{P}$ and $\mathbf{O}$ as precoders and interchangeably.

From (6), the received frequency domain signal for the k^{th} OFDM symbol can be equivalently expressed as

$$\mathbf{Y}_k = \mathbf{Q}(\mathbf{H} - \mathbf{A})\mathbf{Q}^H \mathbf{P}\mathbf{x}_k + \mathbf{Q}\mathbf{B}\mathbf{Q}^H \mathbf{P}\mathbf{x}_{k-1} + \tilde{\mathbf{w}}_k. \quad (8)$$

B. MIMO-OFDM Model

By considering a MIMO system with N_t transmit, N_r receive antennas, and by using the signal model in the SISO-OFDM system, the model of OFDM with insufficient CP is further extended to MIMO-OFDM in spatial multiplexing mode.

At each antenna, a CP of length G is added to the input signal symbol and propagates via a multipath channel $\mathbf{h}_{ij} = [h_{ij}(0), h_{ij}(1), \dots, h_{ij}(L-1)]^T$ between the i^{th} receive antenna and the j^{th} transmit antenna, where we assume that all the

entries of h_{ij} are i.i.d. complex Gaussian random variables with zero mean and the channel length, L is identical for all the channels. We now define $N_r \times N_t$ channel matrices $\mathbf{H}(l), l = 0, 1, \dots, L-1$ as

$$\mathbf{H}(l) = \begin{bmatrix} h_{11}(l) & h_{12}(l) & \dots & h_{1N_t}(l) \\ h_{21}(l) & h_{22}(l) & \dots & h_{2N_t}(l) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1}(l) & h_{N_r2}(l) & \dots & h_{N_rN_t}(l) \end{bmatrix}. \quad (9)$$

These matrices $\mathbf{H}(l), l = 0, 1, \dots, L-1$ are the multipath channel matrices for the time domain vector $\mathbf{D}_k^i$ serially transmitted at N_t transmit antennas. Due to the randomness of the channel coefficients, all the matrices $\mathbf{H}(l)$ are of full rank almost surely. At the receiver, the CP is removed and the overall time domain received signal is given by

$$\bar{\mathbf{y}}_k = (\mathbf{H} - \mathbf{A})\bar{\mathbf{Q}}\bar{\mathbf{D}}_k + \bar{\mathbf{B}}\bar{\mathbf{Q}}\bar{\mathbf{D}}_{k-1} + \mathbf{w}_k, \quad (10)$$

where $\mathbf{w}_k$ is the $NN_r \times 1$ noise vector with complex Gaussian distribution $\mathcal{CN}(0, \sigma^2 \mathbf{I})$, $\mathbf{H}, \mathbf{A}$ and $\mathbf{B}$ of size $NN_r \times NN_t$ are the overall channel matrix and ICI matrix, respectively. For convenience of the designing the precoding matrix, we consider the design of precoder $\mathbf{O} = \bar{\mathbf{Q}}\mathbf{P}$. The precoding matrix $\mathbf{P}$ can be obtained by multiplying $\mathbf{O}$ with $\bar{\mathbf{Q}}^{-1} = \mathbf{Q} \otimes \mathbf{I}_{N_r}$. Thus, both $\mathbf{P}$ and $\mathbf{O}$ are called precoders interchangeably. Finally, we can represent the received frequency domain of the OFDM symbol as

$$\bar{\mathbf{Y}}_k = (\mathbf{Q} \otimes \mathbf{I}_{N_r})(\mathbf{H} - \mathbf{A})\bar{\mathbf{O}}\bar{\mathbf{x}}_k + (\mathbf{Q} \otimes \mathbf{I}_{N_r})\bar{\mathbf{B}}\bar{\mathbf{O}}\bar{\mathbf{x}}_{k-1} + \tilde{\mathbf{w}}_k \quad (11)$$

III. SYSTEM DESIGN

From equation (8), we assume that

$$y[k] = ax[k] + bx[k-1], \quad (12)$$

Using the Z-transform, we obtain $\mathbf{Y}(z) = a\mathbf{X}(z) + b\mathbf{X}(z)z^{-1}$. From above equation, we will know the channel transfer function which equal to the ration of output signal over the input signal.

$$\mathbf{H}^{-1}(z) = \frac{1}{a + bz^{-1}}. \quad (13)$$

The precoding or the inverse system has input-output relationship. Note that $x[k]$ is the input, $y[k]$ is the output. From $\mathbf{Y}(z) = \mathbf{H}^{-1}(z)\mathbf{X}(z)$, we can be written as

$$ay[k] + by[k-1] = x[k]. \quad (14)$$

From (14), we want the output signal and can be rewritten as

$$ay[k] = x[k] - by[k-1], \quad (15)$$

$$y[k] = \frac{1}{a} \{x[k] - by[k-1]\}. \quad (16)$$

By using the pattern matching, the receive frequency domain signal for the SISO-OFDM system can be written as

$$\mathbf{Y}_k = \mathbf{Q}(\mathbf{H} - \mathbf{A})\mathbf{Q}^H \mathbf{D}_k + \mathbf{Q}\mathbf{B}\mathbf{Q}^H \mathbf{D}_{k-1}, \quad (17)$$

Thus, we obtain

$$\mathbf{P} = [\mathbf{Q}(\mathbf{H} - \mathbf{A})\mathbf{Q}^H]^{-1}, \quad (18)$$

and

$$\mathbf{E} = -\mathbf{Q}\mathbf{B}\mathbf{Q}^H. \quad (19)$$

In this paper, we focus on the downlink transmissions from the base station to the mobile users. The CP is insufficient, we have $G \leq L \leq N$ where G is the length of the cyclic prefix, L is the length of the CIR. The system model with insufficient cyclic prefix is presented in figure 2.

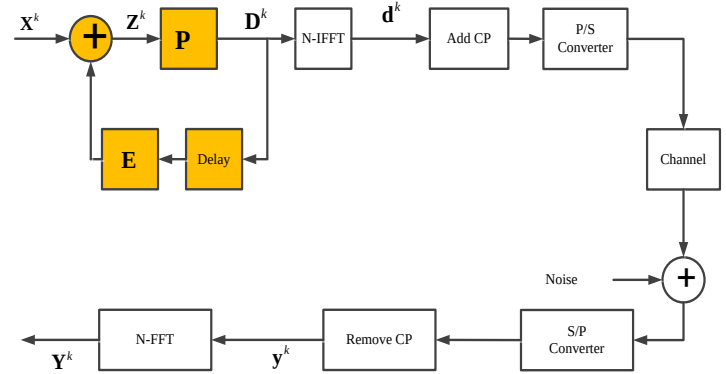


Figure 2 Precoder model with insufficient cyclic prefix.

The information symbol vector denotes by $\mathbf{X}$. We defined $\mathbf{X}^k(n, m)$, where $m \in \{0, \dots, M-1\}$, $n \in \{0, \dots, N-1\}$, $k \in \mathbb{Z}^+$ be the QPSK symbol on subchannel m of subcarrier n of the OFDM symbol k . The information symbol vector is denoted by $\mathbf{X}^k = [(\mathbf{X}_1^k)^T, (\mathbf{X}_2^k)^T, \dots, (\mathbf{X}_{N_t}^k)^T]^T$, where $\mathbf{X}_j^k = [\mathbf{X}_j^k(0), \mathbf{X}_j^k(1), \dots, \mathbf{X}_j^k(N-1)]^T$, $j = 0, 1, \dots, N_t$. The precoded symbols are denoted by $\mathbf{D}^k = [(\mathbf{D}_1^k)^T, (\mathbf{D}_2^k)^T, \dots, (\mathbf{D}_{N_t}^k)^T]^T$, where $\mathbf{D}_j^k = [\mathbf{D}_j^k(0), \mathbf{D}_j^k(1), \dots, \mathbf{D}_j^k(N-1)]^T$, $j = 0, 1, \dots, N_t$. $\mathbf{D}_j^k(n)$ represents the precoded value at j^{th} antenna on subcarrier n of k^{th} OFDM

symbol. The output of the IFFT matrix in the time domain is given by

$$\mathbf{d}_j^k = \mathbf{Q}^H \mathbf{D}_j^k = \mathbf{Q}^H \mathbf{P}(\mathbf{X}_j^k + \mathbf{E} \mathbf{D}_j^{k-1}) , \quad (20)$$

where $\mathbf{Q}^H$ is the IFFT matrix of size N . The transmitted OFDM symbol is affected by both ICI and ISI components. At i^{th} receive antenna, after the cyclic prefix is removed, in time domain is written as

$$\mathbf{y}_i^k = \sum_{j=1}^{N_t} \mathbf{h}_{ij} \mathbf{Q}^H \mathbf{D}_j^k - \sum_{j=1}^{N_t} \mathbf{a}_{ij} \mathbf{Q}^H \mathbf{D}_j^k + \sum_{j=1}^{N_t} \mathbf{b}_{ij} \mathbf{Q}^H \mathbf{D}_j^{k-1} + \mathbf{w}_i^k , \quad (21)$$

where $\mathbf{w}_i^k$ denotes the time domain received noise vector at i^{th} receive antenna with distribution $\mathcal{CN}(0, \sigma^2 \mathbf{I})$. $\mathbf{h}_{ij}$ is the channel matrix between the j^{th} transmit and i^{th} receive antenna. $\mathbf{a}_{ij}$ and $\mathbf{b}_{ij}$ are the ICI and ISI components of the channel, respectively. If G is longer than L , $\mathbf{a}_{ij}$ and $\mathbf{b}_{ij}$ are zeros, thus no ICI and ISI exists in the receive signal.

At the i^{th} receive antenna, the time domain signal $\mathbf{y}_i^k$ is transformed into the frequency domain signal $\mathbf{Y}_i^k$ by the FFT matrix $\mathbf{Q}$ of size N .

$$\mathbf{Y}_i^k = \sum_{j=1}^{N_t} \mathbf{Q} \mathbf{h}_{ij} \mathbf{Q}^H \mathbf{D}_j^k - \sum_{j=1}^{N_t} \mathbf{Q} \mathbf{a}_{ij} \mathbf{Q}^H \mathbf{D}_j^k + \sum_{j=1}^{N_t} \mathbf{Q} \mathbf{b}_{ij} \mathbf{Q}^H \mathbf{D}_j^{k-1} + \mathbf{Q} \mathbf{w}_i^k . \quad (22)$$

The receive frequency domain signal for the MIMO-OFDM system of the k^{th} OFDM symbol can be written as:

$$\mathbf{Y}^k = \tilde{\mathbf{Q}} \mathbf{h} \mathbf{Q}^H \mathbf{D}^k - \tilde{\mathbf{Q}} \mathbf{a} \mathbf{Q}^H \mathbf{D}^k + \tilde{\mathbf{Q}} \mathbf{b} \mathbf{Q}^H \mathbf{D}^{k-1} + \tilde{\mathbf{Q}} \mathbf{w}_i^k , \quad (23)$$

where $\mathbf{h}, \mathbf{a}$ and $\mathbf{b}$ are the stacked matrices of $\mathbf{h}_{ij}, \mathbf{a}_{ij}$ and $\mathbf{b}_{ij}$ representing the channel matrix, ICI and ISI matrices, respectively. Both $\tilde{\mathbf{Q}}^H$ and $\tilde{\mathbf{Q}}$ are the IFFT and FFT matrices, which are given as $\tilde{\mathbf{Q}}^H = \mathbf{Q}^H \otimes \mathbf{I}_{N_t}$ and $\tilde{\mathbf{Q}} = \mathbf{Q} \otimes \mathbf{I}_{N_r}$, respectively.

The basic scheme is drawn in figure 3. The channel transfer function is known to both the transmitter and receiver. We assume that the channel transfer function is stable and not zeros. $\mathbf{P}$ and $\mathbf{E}$ are block filters. We described the precoding and show how the precoding removes the ISI and ICI caused by insufficient cyclic prefix length. We assume that the CIR is shorter than N , where N is the number of subcarriers $(0, 1, \dots, N-1)$.

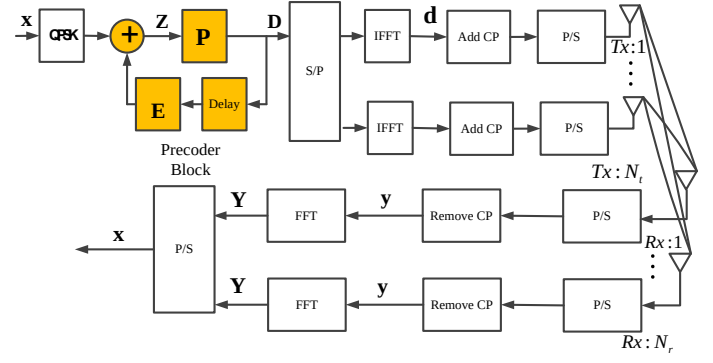


Figure 3 MIMO-OFDM with Insufficient Cyclic Prefix.

At the receiver, neglecting additive noise, the CP is removed and the time domain received signal is given,

$$\mathbf{y}^k = (\mathbf{h} - \mathbf{a}) \tilde{\mathbf{Q}}^H \mathbf{D}^k + \mathbf{b} \tilde{\mathbf{Q}}^H \mathbf{D}^{k-1} . \quad (24)$$

In order to find the $\mathbf{P}$ and $\mathbf{E}$ matrices, we use the Z-transform to help in considering for the discrete-time signal. The receive frequency domain signal for the MIMO-OFDM system in the k^{th} OFDM symbol can be written as

$$\mathbf{Y}^k = \tilde{\mathbf{Q}} (\mathbf{h} - \mathbf{a}) \tilde{\mathbf{Q}}^H \mathbf{D}^k + \tilde{\mathbf{Q}} \mathbf{b} \tilde{\mathbf{Q}}^H \mathbf{D}^{k-1} . \quad (25)$$

We can write the input-output relationship for the inverse system, i.e., zero-forcing. From which, we obtain

$$\mathbf{P} = \left[\tilde{\mathbf{Q}} (\mathbf{h} - \mathbf{a}) \tilde{\mathbf{Q}}^H \right]^{-1} , \quad (26)$$

$$\text{and} \quad \mathbf{E} = -\tilde{\mathbf{Q}} \mathbf{b} \tilde{\mathbf{Q}}^H . \quad (27)$$

IV. SIMULATION RESULTS

The simulation parameters of this paper are given in Table 1.

Table 1 Simulation parameters

Parameter	Notation	Value
The length of CIR	L	8,16,32
The length of CP	G	4,8,16
Number of transmit antenna	N_t	1,2
Number of receive antenna	N_r	1,2
Number of subcarrier	N	16,32,64
OFDM symbol		1,000
CIR parameter of SISO	h	0.7
CIR parameter for MIMO	$\begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix}$	$\begin{bmatrix} 0.8 & 0.7 \\ 0.6 & 0.5 \end{bmatrix}$

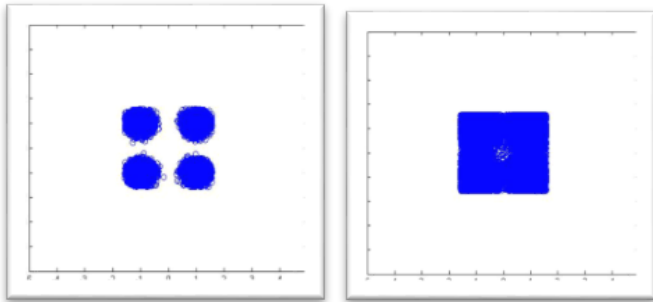


Figure 4 Signal Constellation for SISO-OFDM with
(a) Precoder (b) No Precoder

In figure 4, the signal constellations of SISO-OFDM with precoder and no precoder are presented. We notice that by using precoder technique, we can justify the correct signal constellation which is equal to $1+i, 1-i, -1+i, -1-i$. However, the bit error rate (BER) by using precoder is less than no precoder.

In figure 5 shows BER of SISO-OFDM. We notice that the BER of SISO-OFDM using precoding technique with insufficient cyclic prefix length is less than for SISO-OFDM with sufficient cyclic prefix with one-tap equalization. We observe that BER of SISO-OFDM precoding with sufficient cyclic prefix is as same as of SISO-OFDM precoding with insufficient cyclic prefix length. We can see that the BER of MIMO-OFDM using precoding technique with insufficient cyclic prefix length is lower than MIMO-OFDM with sufficient cyclic prefix with SVD one-tap. For example, at BER 10^{-4} using insufficient cyclic prefix length has less SNR about 13 dB as compare with MIMO-OFDM with sufficient cyclic prefix length for one-tap SVD.

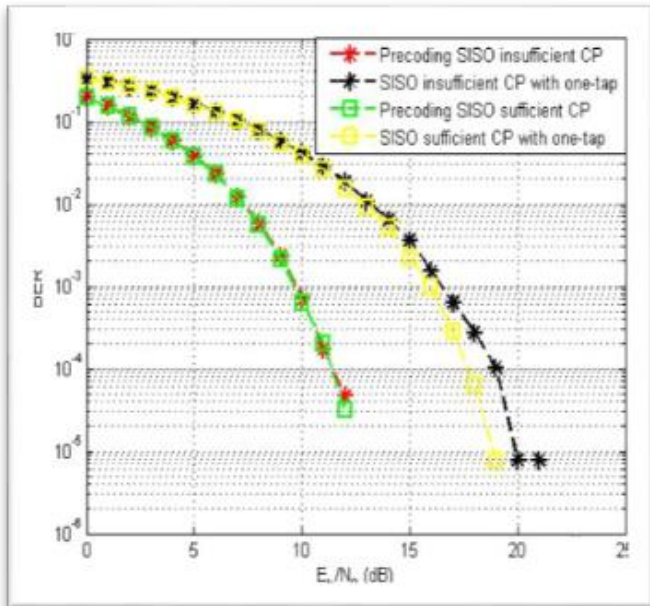


Figure 5 BER of SISO-OFDM with sufficient and insufficient cyclic prefix length using precoding and one-tap equalizer.

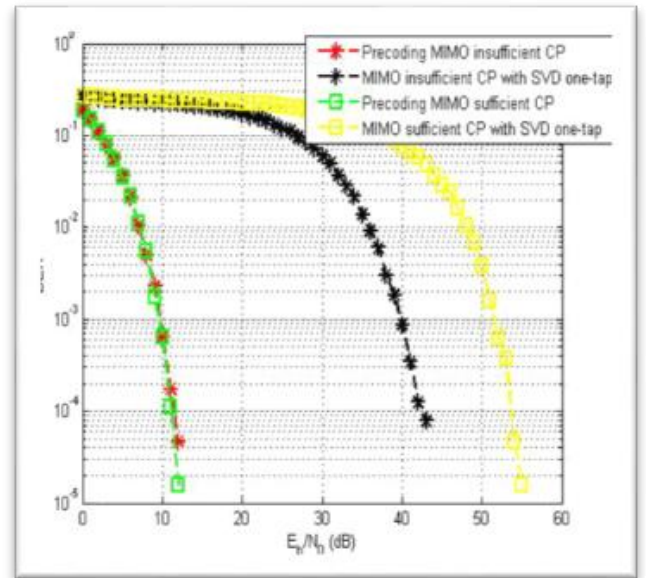


Figure 6. BER of MIMO-OFDM with sufficient and insufficient cyclic prefix length using precoding and one-tap equalizer.

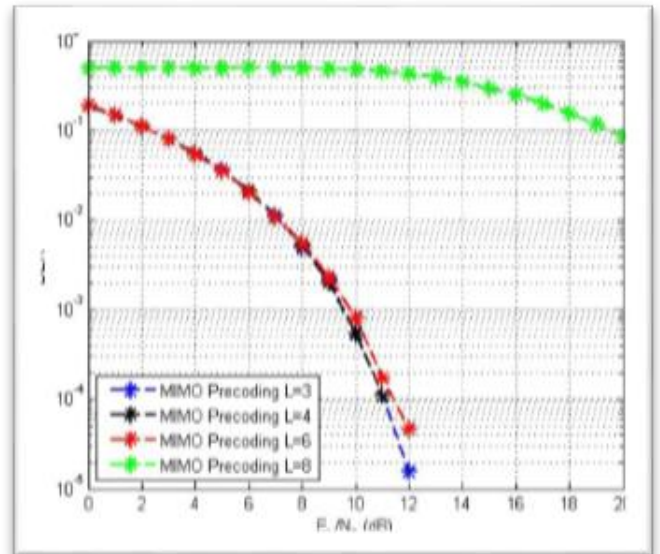


Figure 7. BER of MIMO-OFDM with insufficient cyclic prefix length at the different values of channel impulse response.

We notice that BER of MIMO-OFDM precoding with sufficient cyclic prefix is as same as of MIMO-OFDM precoding with insufficient cyclic prefix length. We observe that the less channel impulse response length the better BER as presented in Figure 8. However when we increase the value of subcarriers of OFDM, the system performance is obtain.

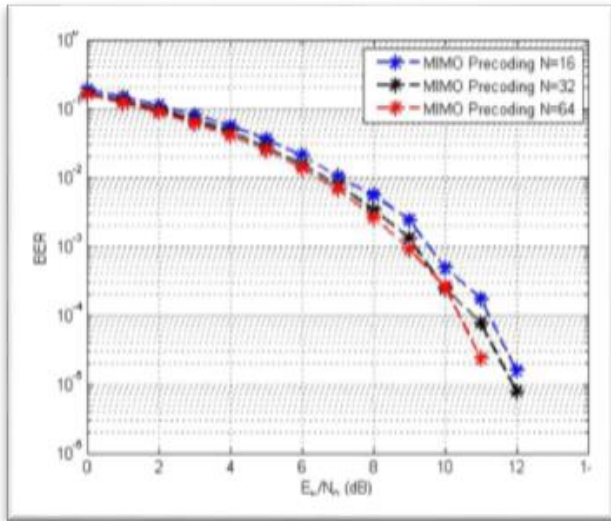


Figure 8. BER of MIMO-OFDM with insufficient cyclic prefix length at the different values of subcarriers.

V. CONCLUSION

We propose channel dependent precoding for MIMO-OFDM systems with insufficient CP. In order to eliminate ISI and ICI owing to insufficient CP, precoding is performed at the transmitter. Precoding matrices are derived base on the zero-forcing equalization criterion. The modulo operation is perform. Simulation results indicate that the precoding technique is much more efficient the conventional OFDM with one-tap equalization in term of the required SNR for the same BER. In addition, the precoding technique can be applied to both sufficient CP and insufficient CP. Simulation results indicate that the precoding technique is much more efficient the conventional OFDM with one-tap equalization in term of the required SNR for the same BER. In addition, the precoding technique can be applied to both sufficient CP and insufficient CP.

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