Channel Estimation and ISI/ICI Cancellation for MIMO-OFDM Systems with Insufficient Cyclic Prefix

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Abstract. In multi-input multi-output orthogonal frequency division multiplexing (MIMO-OFDM) systems, the multipath components whose delays exceed cyclic prefix (CP) cause inter-symbol interference (ISI) and inter-carrier interference (ICI), which may degrade system performance severely. In this paper, we propose a joint channel estimation and ISI/ICI cancellation scheme in which a limited CP is used in a trade-off against high-rate performance in MIMO-OFDM systems. A channel estimation scheme based on the criterion of Expectation-Maximization (EM) algorithm can be proposed through the use of a training symbol. The EM algorithm uses an iterative procedure to estimate channel parameters and can estimate channel impulse response (CIR) accurately enough to mitigate ISI/ICI influences. Through the accurate CIR estimation, an efficient method has been developed to counteract ISI/ICI influences in signal detection in the case where the inserted CP length is less than the CIR length. Simulation results show that the proposed method can significantly enhance the overall MIMO-OFDM system performance after only a few iterations.

Keywords: multi-input multi-output orthogonal frequency division multiplexing (MIMO-OFDM), inter-symbol interference (ISI), inter-carrier interference (ICI), Expectation-Maximization (EM) algorithm.

1 Introduction

Orthogonal frequency division multiplexing (OFDM) is an attractive technique for high-speed data transmission in mobile communications [1], [2]. In OFDM, the computationally efficient Fast Fourier Transform (FFT) algorithm is used to transmit data in parallel over a large number of orthogonal subcarriers. At the transmitter, the OFDM modulator appends at each symbol block head a cyclic prefix (CP), with length no shorter than the channel impulse response (CIR) interval, for removing inter-symbol interference (ISI). When an adequate number of subcarriers are used in conjunction with a CP of adequate length, subcarrier orthogonality is maintained if the channel is time invariant within an OFDM symbol. For many high data rate systems, the addition of a CP can cause more than a bandwidth expansion, which is a very significant loss of a valuable resource. Therefore, the CP interval should not be

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too large a fraction of the OFDM symbol interval. Since the use of CP results in a lowering of spectral efficiency, several approaches have been proposed to cope with this problem. OFDM combined with multiple transmit and receive antennas, a.k.a. multi-input multi-output (MIMO) OFDM, has become a key communication technique over frequency-selective fading channels [3]. In [4], a well-known MIMO-OFDM system called V-BLAST (Vertical Bell Laboratories Layered Space-Time) was proposed for realizing very high data rates. However, interference from other antennas causes the receiver performance to degrade. Also, when the CP is not longer than the CIR in MIMO-OFDM system, ISI and inter-carrier interference (ICI) will greatly affect the receiver performance. A commonly used approach to boost the transmission rate in MIMO-OFDM is thus to conserve the length of CP, and rely on sophisticated receiver design to combat the residual ISI as well as the induced ICI.

One conventional approach is to employ a time-domain equalizer (TEQ) to reduce the duration of the overall response of the transmission system [5]. However, the TEQ technique involves intensive computational complexity, and the optimum design of TEQ turns out to be a difficult task [6]. The frequency-domain equalization method proposed in [7] offers a decision feedback equalizer based on tentative decisions. Other methods include the time-domain channel shortening mechanism [8] and the frequency-domain per-tone equalization scheme [9]. The former resorts to a shortening filter for "squeezing" the composite channel memory within the CP interval, thus limiting the ISI effect; the latter, on the other hand, aims at direct ISI and ICI suppression in the frequency domain. Both of the above methods assume perfect channel information is available at the receiver. However, channel parameter mismatch due to imperfect estimation is inevitable in practice, and can further impair the system performance.

In this paper, we propose a joint channel estimation and ISI/ICI cancellation scheme when a limited CP is used in a trade-off against high-rate performance in MIMO-OFDM systems. A channel estimation scheme can be proposed through the use of a training symbol which is based on the criterion of Expectation-Maximization (EM) algorithm. The EM algorithm is an iterative procedure to estimate channel parameters and it can estimate CIR accurately enough to mitigate ISI/ICI influence. By the accurate CIR estimation, an efficient method has been developed to counteract ISI/ICI influence for signal detection in the case where the inserted CP length is less than the CIR interval. After both the ISI and ICI are cancelled in MIMO-OFDM signals, the QR decomposition (QRD)-M algorithm [10] will be used for signal detection.

2 Signal Model

A typical baseband model of a MIMO-OFDM system is illustrated in Fig. 1. Consider a MIMO–OFDM system with N_T transmit antennas, N_R receive antennas, and N subcarriers, which employs quadrature amplitude modulation (QAM). The original data stream is encoded by a 1/2-rate convolutional coder, and the coded data stream is interleaved using the method defined by [11] and then each coded bit is mapped into one QAM symbol. After modulation, the QAM symbols are fed to an N-point inverse discrete Fourier transform (IDFT) to produce the OFDM signal, and a CP of length G is inserted in front of each OFDM symbol as a guard interval. Let $\mathbf{x}_i^k$ represents the

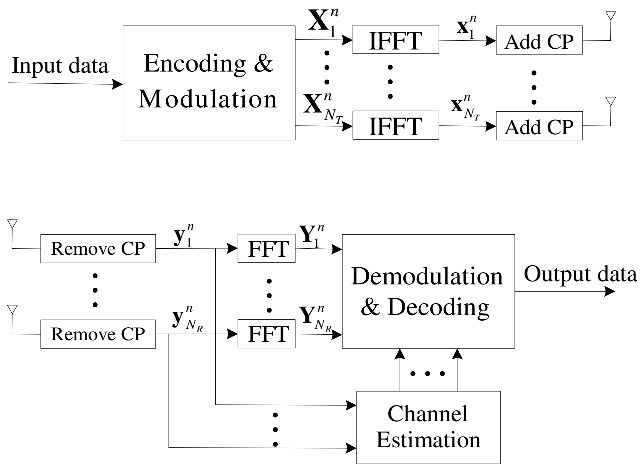

Fig. 1. Structure of a MIMO-OFDM system

time-domain OFDM signal vector transmitted at i-th transmit antennas during the time k, where $\mathbf{x}_i^k = \left[x_i^k(0) \ x_i^k(1) \ \dots \ x_i^k(N-1) \right]^T$, $1 \le i \le N_T$. The OFDM symbols are transmitted through the multipath fading channel corrupted by additive white Gaussian noise (AWGN) noise. Let $\mathbf{h} = \left[h(0), \ h(1), \cdots, h(L-1) \ \right]^T$ denote the channel impulse response, where L is the channel length.

Fig.2 depicts the scenario in the receiver highlighting the different propagation delays for each path. In the system model, we consider that the received signal includes the multipath components with the delay time greater than CP. As highlighted by the shaded regions in Fig. 2, the OFDM symbols appearing at the receiver are spread by the multipath channel, resulting in ISI and ICI. The interferences have to be cancelled for successful demodulation of the symbol within the receiver FFT window. Notice that we assume that there is perfect synchronization, L is smaller than N and the channel is time-invariant within a burst. At the receiver, CP is removed after A/D conversion. In the absence of noise, if the CP length G is shorter than the maximum channel delay spread L, i.e., $G<L$, the received time-domain signal vector at the j-th received antenna during the time k is

$$\mathbf{y}_j^k = \sum_i \left\{ \mathbf{H}_{j,i}^k \mathbf{x}_i^k - \mathbf{A}_{j,i}^k \mathbf{x}_i^k + \mathbf{B}_{j,i}^k \mathbf{x}_i^{k-1} \right\} + \boldsymbol{\eta}_j^k \tag{1}$$

where $\mathbf{y}_j^k = [\mathbf{y}_i^k(0), \mathbf{y}_i^k(1), \cdots, \mathbf{y}_i^k(N-1)]^T$ is a signal vector which contains the N consecutive received samples and $\boldsymbol{\eta}_j^k = [\boldsymbol{\eta}_j^k(0), \boldsymbol{\eta}_j^k(1), \cdots, \boldsymbol{\eta}_j^k(N-1)]^T$, which is a color noise vector. Notice that the matrices **A** and **B** are N x N matrices that result from excess channel responses. The matrix **H** is an N x N circular matrix of CIR and the last (L-G) columns of **A** are zeros [12]. These matrices can be formed as in (2). Therefore, the first term of the right-hand side in (1) indicates the part of signal which

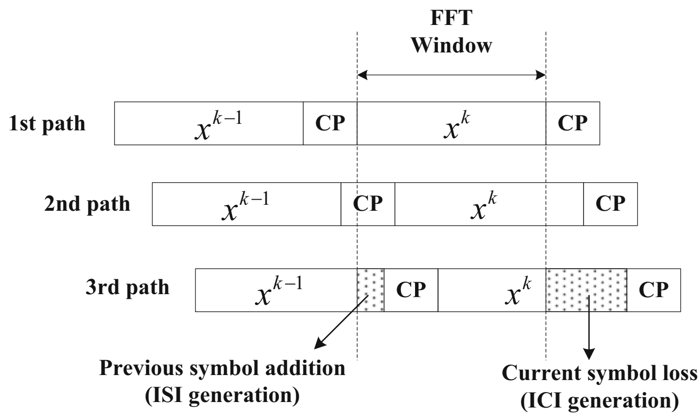

Fig. 2. Received signal model combining ISI and ICI due to long delay path

is free of ISI and ICI (assuming that the CP interval is long enough). The second term indicates the ICI part which has been added to the matrix A due to $G<L$. The third term shows the ISI part due to interference of previous OFDM symbol. If G is not smaller than L, all samples of the sequence are free of interference i.e., **A** and **B** are zero matrices, and thus neither ICI nor ISI exists. However, if the CP length is insufficient, the residual of length equal to L minus G induces ICI within the current symbol and the ISI from previous symbol. Since ISI and ICI may degrade the system performance severely, a measure must be taken to counteract these interferences when the CP length is insufficient.

$$\mathbf{H} = \begin{bmatrix} h(0) & 0 & \cdots & 0 & h(L-1) & \vdots & \vdots & h(1) \\ h(1) & h(0) & 0 & \vdots & 0 & h(L-1) & \vdots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots & 0 & h(L-1) & \vdots \\ h(L-1) & h(L-2) & \ddots & h(0) & 0 & \vdots & 0 & h(L-1) \\ 0 & h(L-1) & h(L-2) & \ddots & h(0) & 0 & \vdots & 0 \\ 0 & 0 & \ddots & \vdots & h(1) & h(0) & 0 & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots & h(1) & h(0) & 0 \\ 0 & 0 & 0 & h(L-1) & h(L-2) & \cdots & h(1) & h(0) \end{bmatrix}_{N\times N}$$

$$\mathbf{A} = \begin{bmatrix} 0 & h(L-1) & \ddots & \vdots & h(G) & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \vdots & h(G+1) & 0 & \ddots & 0 \\ \vdots & 0 & 0 & h(L-1) & \vdots & 0 & \ddots & 0 \\ 0 & \vdots & 0 & 0 & h(L-1) & 0 & \ddots & 0 \\ 0 & \ddots & \vdots & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & \ddots & \vdots & 0 & 0 & \ddots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times N}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & \cdots & 0 & h(L-1) & \ddots & \cdots & h(G) \\ 0 & 0 & \ddots & \vdots & 0 & h(L-1) & \ddots & h(G+1) \\ \vdots & 0 & 0 & 0 & \vdots & 0 & \ddots & \vdots \\ 0 & \vdots & 0 & 0 & 0 & 0 & \ddots & h(L-1) \\ 0 & \ddots & \vdots & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & \ddots & \vdots & 0 & 0 & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times N} \quad (2)$$

3 Proposed Channel Estimation with EM Algorithm and ISI/ICI Cancellation

The channel estimation is a complicated multi-parameter estimation problem. In our systems, one OFDM training symbol is transmitted from each transmit antenna for EM-based channel estimation at the receiver. One training sequence is transmitted from each transmit antenna for MIMO channel estimation at the receiver. In IEEE 802.11n TGn Sync proposal [5], preamble (training sequence) transmitted from different transmit antenna will be allocated in different sub-carriers in order not to interfere with preamble signals from other transmit antennas. Consequently, we can regard our 2 x 2 MIMO-OFDM systems as four SISO-OFDM systems during channel estimation. However, channel estimation at the receiver should decompose the mixed signals into four individual signals. The EM algorithm is an iterative method to estimate channel parameters. In order to reduce complexity, based on the EM algorithm we jointly estimate channel responses of four paths from each individual received signal vectors, $\mathbf{h}_{j,i}^k$ using least-squares (LS) algorithm.

Based on the signal model (1), we can express the signal model in frequency domain by multiplying by a discrete Fourier transform (DFT) matrix as

$$\mathbf{Y}_j^k = \mathbf{W}\mathbf{y}_j^k = \sum_i \left\{ \mathbf{W}\mathbf{H}_{j,i}^k \mathbf{x}_i^k - \mathbf{W}\mathbf{A}_{j,i}^k \mathbf{x}_i^k + \mathbf{W}\mathbf{B}_{j,i}^k \mathbf{x}_i^{k-1} \right\} + \mathbf{\Lambda}_j^k , \quad (3)$$

where the DFT matrix is defined as $\mathbf{W}[n,l] = e^{-2\pi nl/N}$, $0 \le n \le N-1,\ 0 \le l \le N-1$ and $\mathbf{\Lambda}_j^k$ is AWGN noise vector in frequency domain. Note that, in equation (3), the OFDM signal in time domain can be expressed as

$$\mathbf{x}_i^k = \frac{1}{N}\mathbf{W}^H \mathbf{X}_i^k \ \text{ where } \mathbf{X}_i^k = \left[X_i^k(0), X_i^k(1), ..., X_i^k(N-1), \right]^T,$$

$$N: \text{number of subcarriers.} \quad (4)$$

Thus, the frequency-domain signal model is

$$\begin{aligned} \mathbf{Y}_j^k &= \sum_i \{ \frac{1}{N}\mathbf{W}\mathbf{H}_{j,i}^k \mathbf{W}^H \mathbf{X}_i^k - \frac{1}{N}\mathbf{W}\mathbf{A}_{j,i}^k \mathbf{W}^H \mathbf{X}_i^k + \frac{1}{N}\mathbf{W}\mathbf{B}_{j,i}^k \mathbf{W}^H \mathbf{X}_i^{k-1} \} + \mathbf{\Lambda}_j^k \\ &= \sum_i \{ diag(\mathbf{X}_i^k)\mathbf{W}_{trun}\mathbf{h}_{j,i}^k - ICI_{j,i}^k + ISI_{j,i}^{k-1} \} + \mathbf{\Lambda}_j^k \end{aligned} \quad (5)$$

where $\mathbf{Y}_j^k$ means that the k-th frequency-domain received signals at the j-th received antenna, $\mathbf{W}_{trun} = e^{-2\pi nl/N}$, $0 \le n \le N-1$, $0 \le l \le L-1$ and $\mathbf{h}_{j,i}^k = \left[h_{j,i}^k(0), h_{j,i}^k(1), \ldots, h_{j,i}^k(L-1)\right]^T$. We decompose the observed data $\mathbf{Y}_j^k$ into its N_T components, $\mathbf{Y}_{j,i}^k = diag(\mathbf{X}_i^k)\mathbf{W}_{trun}\mathbf{h}_{j,i}^k - ICI_{j,i}^k + ISI_{j,i}^{k-1} + \mathbf{\Lambda}_{j,i}^k$, $i = 1, 2, \cdots, N_T$ where $\mathbf{\Lambda}_{j,i}^k$ is component of $\mathbf{\Lambda}_j^k$ with $\sum_{i=1}^{N_T} \mathbf{\Lambda}_{j,i}^k = \mathbf{\Lambda}_j^k$.

The EM-based channel estimation consists of the following steps. Note that the superscript (α) signifies the α-th iteration numbers.

$$for\ j = 1, \ldots, N_R$$

$$E\ step:$$

$$for\ i = 1, \ldots, N_T$$

$$\hat{\mathbf{Y}}_{j,i}^{k^{(\alpha)}} = diag(\mathbf{X}_i^k)\mathbf{W}_{trun}\hat{\mathbf{h}}_{j,i}^{k^{(\alpha)}} + \beta\left\{\mathbf{Y}_j^k - \left[\sum_{i=1}^{N_T}\left(diag(\mathbf{X}_i)\mathbf{W}_{trun}\hat{\mathbf{h}}_{j,i}^{k^{(\alpha)}} - I\hat{C}I_{j,i}^{k^{(\alpha)}} + I\hat{S}I_{j,i}^{k^{(\alpha)}}\right)\right]\right\}$$

$$End$$

$$M\ step:$$

$$for\ i = 1, \ldots, N_T$$

$$\hat{\mathbf{h}}_{j,i}^{k^{(\alpha+1)}} = \frac{1}{N}\mathbf{W}_{trun}^H diag(\mathbf{X}_i)^{-1}\hat{\mathbf{Y}}_{j,i}^{k^{(\alpha)}}$$

$$End$$

$$End$$

$$Update\ ISI / ICI:$$

$$for\ j = 1, \ldots, N_R$$

$$for\ i = 1, \ldots, N_T$$

$$I\hat{C}I_{j,i}^{k^{(\alpha+1)}} = \frac{1}{N}\mathbf{W}_{trun}\mathbf{A}_{j,i}^{k^{(\alpha+1)}}\mathbf{W}_{trun}^H\mathbf{X}_i^k$$

$$I\hat{S}I_{j,i}^{k^{(\alpha+1)}} = \frac{1}{N}\mathbf{W}_{trun}\mathbf{B}_{j,i}^{k^{(\alpha+1)}}\mathbf{W}_{trun}^H\mathbf{X}_i^{k-1}$$

$$End$$

$$End$$

where β is a real-valued scalar that satisfies

$$\sum_{i=1}^{N_T} \beta_i = 1(\beta_i \geq 0)\,. \tag{6}$$

This method aims at cancelling the ISI and ICI interferences before the signal detection at the receiver. We find a method to reduce the effects of ISI and ICI without knowledge of transmitted symbols a priori. We assume that channel estimation is accurate, which was discussed in the last paragraph. With channel estimates available, we use the previous OFDM symbol, $\mathbf{x}_i^{k-1}$ to calculate the ISI term $\sum_{i=1}^{N_T} \mathbf{B}_{j,i}^k \mathbf{x}_i^{k-1}$ and subtract it from the received signal, $\mathbf{y}_j^k$ as

$$\begin{aligned} \hat{\mathbf{y}}_j^k &= \mathbf{y}_j^k - \sum_{i=1,2,\cdots,N_T} \mathbf{B}_{i,j}^k \mathbf{x}_i^{k-1} \\ &= \sum_{i=1,2,\cdots,N_T} (\mathbf{H}_{j,i}^k \mathbf{x}_i^k - \mathbf{A}_{j,i}^k \mathbf{x}_i^k) + \boldsymbol{\eta}_j^k \end{aligned} \tag{7}$$

Similarly, we perform ICI cancellation by calculating the ICI term, $\sum_{i=1}^{N_T} \mathbf{A}_{j,i}^k \mathbf{x}_i^k$ from a coarse estimate of the current symbol, $\hat{\mathbf{x}}_i^k$ based on available channel estimates and add it to the received signal $\hat{\mathbf{y}}_j^k$ as

$$\begin{aligned} \tilde{\mathbf{y}}_j^k &= \hat{\mathbf{y}}_j^k + \sum_{i=1,2,\cdots,N_T} \mathbf{A}_{j,i}^k \hat{\mathbf{x}}_i^k \\ &= \sum_{i=1,2,\cdots,N_T} \mathbf{H}_{j,i}^k \mathbf{x}_i^k + \boldsymbol{\eta}_j^k \end{aligned} \tag{8}$$

Consequently, $\tilde{\mathbf{y}}_j^k$ is the signal free of interferences (after removing the ISI and ICI influences). Note that, ICI cancellation needs the current detected symbol. Thus, we can redo ICI cancellation over and over again each time using a more and more precise current detected symbol $\hat{\mathbf{x}}_i^k$ based on (8). So ICI cancellation can be an iterative process. After ISI and ICI cancellation are done, we apply the QRD-M algorithm to detect signals, hoping to achieve near-maximum-likelihood (ML) performance with acceptable computational complexity [10].

4 Simulation Results

Simulations have been conducted to clarify the effectiveness of proposed schemes in a 2x2 MIMO-OFDM system. We used 64 subcarriers and a 64-point IFFT/FFT. The original data stream was encoded by a 1/2-rate convolutional coder and the 64 QAM

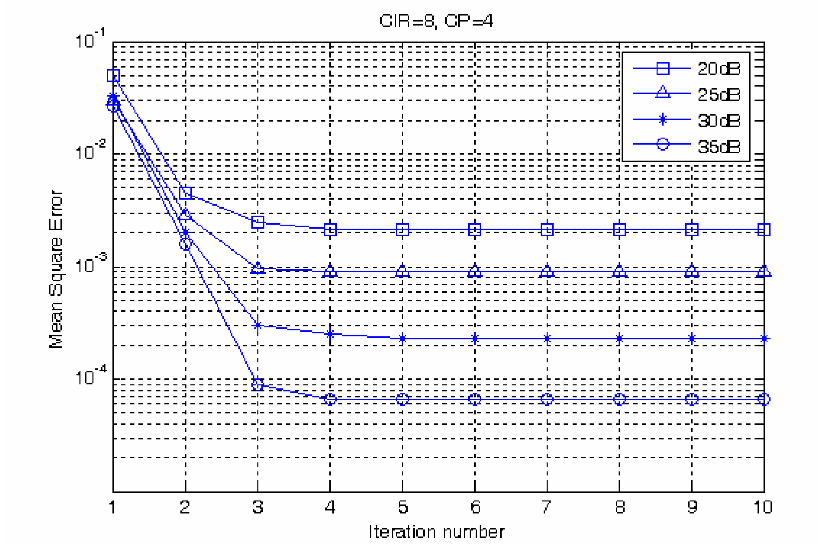

Fig. 3. Convergence performance of the proposed method for different SNR when CP interval is shorter than the CIR interval

modulation scheme was adopted for transmitting data and training sequence. CP of length $G = 4$ was used for high spectral efficiency although a sufficient CP length was used for calculation of the performance lower bound. The multipath channel models in simulations were signal samples from 8 taps ($L = 8$) with rms delay spread of 200ns. These channel models represent typical large space environments such as a store or a factory [13]. The channels were slow fading and time-invariant within a burst. Each tap was generated independently according to exponentially power-decaying Rayleigh fading characteristics. The signal-to-noise ratio (SNR) is defined as the ratio of the transmit power to the AWGN power.

Fig. 3 shows that the convergence curves of the proposed method for different SNR values with rms delay spread=200ns when the CP interval is shorter than the CIR interval. This figure shows that the mean-square error (MSE) for the proposed channel estimation method can reach a constant within 3 to 5 iterations. MSE of the channel estimation reaching a constant implies that an estimation error floor exists. It can also be seen that for different SNR values, both the estimation error floor and the convergence speed are different. Fig. 4 shows the BER performances of the proposed channel estimation scheme, the conventional one-tap frequency-domain equalizer scheme and a method considered decision feedback equalizer for ICI cancellation in [7] for 2x2 MIMO-OFDM systems, all for the case when the CP interval is shorter than the CIR interval. It is obvious that the proposed method can significantly improve the BER performance whereas the conventional one-tap equalizer method exhibits an error floor. In addition, the BER performance of the proposed method has only a slight degradation compared with the CP-sufficient MIMO-OFDM system. Further, we consider a more severe condition under which the channel length is three times that of the shortened CP length, i.e., the channel length is twelve and the G is

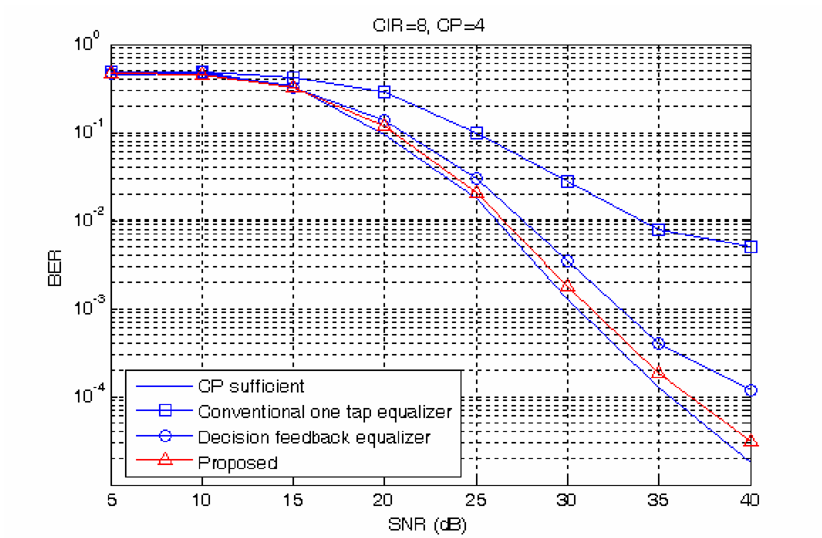

Fig. 4. Comparison of BER performance between the proposed method and other methods when CP interval is shorter than the CIR interval (CIR = 8, CP = 4)

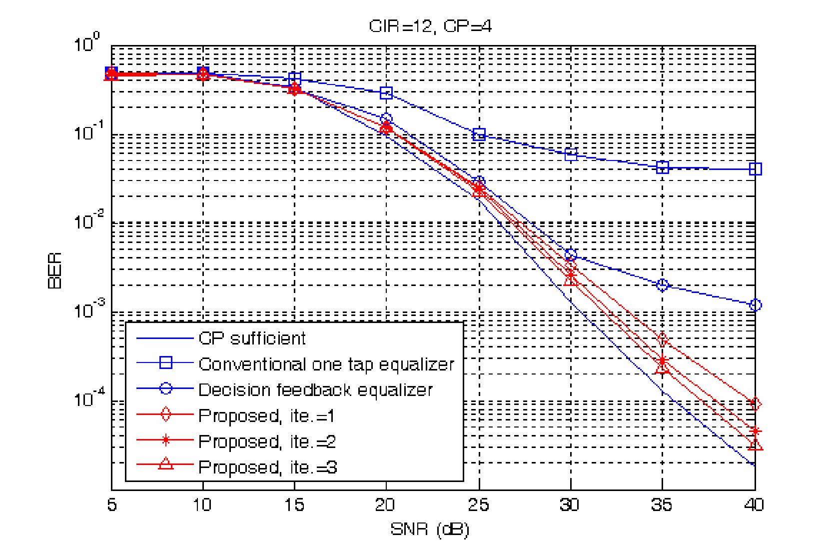

Fig. 5. Comparison of BER performance between the proposed method with the different iterations and other methods when received signal is under severe ISI/ICI influences (CIR = 12, CP = 4).

still four. Fig.5 illustrates that the proposed method can still improve the BER performance whereas the other methods exhibit error floors. However, under such severe conditions, we need more iterations of ICI cancellation to approach the performance of the CP-sufficient system.

5 Conclusion

In this paper, we propose a joint EM-based channel estimation and ISI/ICI cancellation scheme when an insufficient cyclic prefix length is used in a trade-off against high-rate performance in MIMO-OFDM systems. With channel estimation obtained by the EM-based method, the ISI/ICI cancellation is accomplished at low computational cost while giving satisfactory performance. By performing the channel estimation only a few iterations, the proposed scheme can jointly accomplish ISI/ICI cancellation, giving a BER performance approaching that of a CP-sufficient system. Therefore, the proposed scheme is suitable for use for high-speed data transmission in mobile communication systems when high spectral efficiency is required.

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