

A Partial PIC with MRC Receiver Design for SCBT System over Multipath Fading Channels

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Abstract—Single carrier block transmission (SCBT) system has become one of most popular modulation system due to its low peak to average power ratio (PAPR), and it is gradually considered to be used for uplink wireless communication system. And in this paper, for the uplink SCBT system, a low complexity parallel interference cancellation (PIC) with maximum ratio combining (MRC) technology is proposed to use for receiver to combat the inter-carrier interference (ICI) problem over multipath fading channel. With the aid of MRC scheme, the proposed PIC technique can effectively perform the interference cancellation and acquire the benefit of frequency diversity gain. In fact, with more taps for weighting combination, it will lead to higher frequency diversity gain. Furthermore, it indicates that the proposed technique can achieve better bit error rate (BER) performance due to the diversity gain. This can mainly be attributed to the ability of this scheme to effectively deal with interference effects and achieve inherent frequency diversity with MRC. Simulation results reveal that the proposed low complexity PIC-MRC system can provide robust performance and outperform the conventional PIC and the iterative frequency domain decision feedback equalizer (FD-DFE) systems over multipath fading channel environment.

Keywords—single carrier block transmission (SCBT), peak-to-average power ratio (PAPR), maximum likelihood search (MLS), frequency domain decision feedback equalizer (FD-DFE), parallel interference cancellation (PIC), maximum ratio combining (MRC).

I. INTRODUCTION

In the communication area, the technique of digital communications progress so fast, from traditional quadrature phase shift keying (QPSK), time division multiple access (TDMA), to orthogonal frequency division multiplexing (OFDM) system. In order to increase the performance of wireless communication systems, the researchers propose the novel equalizer or signal transmitted method, trying to find the best and effective modulation technique. In recent years, the demands of indoor short-range wireless communications applications for high data rate become great eagerness, e.g., digital home cinema...etc. IEEE 802.15.3c [1] is a high-speed short-range wireless personal area network transmission system standard, which is used for 60 GHz millimeter-wave band environment. Therefore, in order to achieve G bps transmit rate, the requirements of the low PAPR at transmitter, low complexity and excellent BER performances at receiver are very important. Besides, after multipath fading channel,

the multiple streams interference, i.e., parallel signal transmission interference, will be induced for the high data rate system. In order to achieve the requirements and combat the interference problem, many techniques are proposed to realize it, e.g., OFDM and single carrier block transmission (SCBT). For OFDM system, it involves the problem of high PAPR, it will cause power amplifier working in the non-linear area. Thus, it needs to back off output power which will reduce the efficiency of power amplifier. For SCBT system, it is the one of the popular themes in recent years [2]-[4]. It can provide low PAPR performance, so we try to study the interference cancellation technique to provide the excellent BER performance, and reduce the computation complexity at receiver.

References [3] and [4] with the iterative frequency domain decision feedback equalizer (FD-DFE) are proposed for SCBT system. It is noted that the decision and iteration of the FD-DFE scheme are processed on frequency domain. And after more iteration, the performance of BER is improved obviously. Moreover, the BER performance of these systems is performed obviously only when the iterations number is enough high. However, large number of iterations will induce high complexity at the receiver. Parallel interference cancellation (PIC) scheme in [5] can overcome the ICI problem effectively and improve the BER performance obviously. However, it will need more iteration loops to enhance performance for PIC scheme, which will result in high computational complexity at receiver.

Therefore, in order to alleviate the above problem, the PIC with maximum ratio combining (MRC) technique is proposed in this paper. That is, with the aid of MRC scheme [6], the proposed PIC technique can effectively perform the interference cancellation and acquire the benefit of frequency diversity gain. In fact, with more taps for weighting combination, it will lead to higher frequency diversity gain. Furthermore, it indicates that the proposed technique can achieve better BER due to the diversity gain. This can mainly be attributed to the ability of this scheme to effectively deal with interference effects and achieve inherent frequency diversity with MRC. Simulation results reveal that the proposed low complexity PIC-MRC system can provide robust performance and outperform the conventional PIC and the

iterative FD-DFE systems over multipath fading channel environment.

The paper is organized as follows: In Section II, we introduce the system block diagram consisting of frequency domain equalizer and FD-DFE system. In Section III, the PIC with MRC system is proposed. Simulation results of the proposed system are then investigated in Section IV. And the paper is concluded in Section V.

II. SCBT SYSTEM MODEL

A. Frequency Domain Equalization System

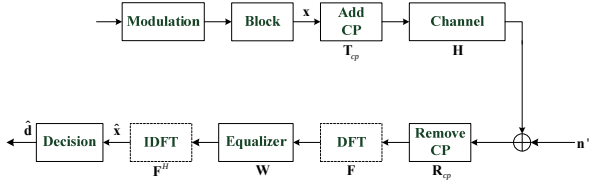


Figure 1. Block diagram of SCBT system.

Figure 1 shows a basic configuration of the SCBT system. First, the n th information signal block of size $N \times 1$ can be defined as

$$\mathbf{x}(n) = [x_0(n), \dots, x_{N-1}(n)]^T \quad (1)$$

where the superscript $(\cdot)^T$ stands for the transpose. The transmitted signal block $\hat{\mathbf{x}}(n)$ of size $(N+K) \times 1$ is generated from $\mathbf{x}(n)$ by adding the cyclic prefix (CP) of K symbols length as the guard interval (GI), namely,

$$\hat{\mathbf{x}}(n) = \mathbf{T}_{cp} \mathbf{x}(n) \quad (2)$$

where $\mathbf{T}_{cp}$ donates the CP insertion matrix of size $(N+K) \times N$ defined as

$$\mathbf{T}_{cp} = \begin{bmatrix} \mathbf{O}_{K \times (N-K)} & \mathbf{I}_{K \times K} \\ \mathbf{I}_{N \times N} & \end{bmatrix}_{(K+N) \times N} \quad (3)$$

$\mathbf{O}_{K \times (N-K)}$ is a zero matrix of size $K \times (N-K)$, and $\mathbf{I}_{N \times N}$ is an identity matrix of size $N \times N$. The received signal block $\hat{\mathbf{y}}(n)$ is written as

$$\hat{\mathbf{y}}(n) = \mathbf{H} \hat{\mathbf{x}}(n) + \mathbf{n}'(n) = \mathbf{h} \otimes_c \hat{\mathbf{x}}(n) + \mathbf{n}'(n) \quad (4)$$

where $\mathbf{n}'(n)$ is a channel noise vector of size $(N+K) \times 1$. $\otimes_c$ is represented as circular convolution, and $\mathbf{h} = \{h_0, \dots, h_{L-1}\}$ denotes the channel impulse response. Next, after discarding the CP portion of the received signal block, the received signal block $\mathbf{y}(n)$ of size $N \times 1$ can be written as

$$\mathbf{y}(n) = \mathbf{R}_{cp} \mathbf{H} \mathbf{T}_{cp} \mathbf{x}(n) + \mathbf{n}(n) \quad (5)$$

where $\mathbf{H}$ is the $(N+K) \times (N+K)$ toeplitz channel matrices $\mathbf{H}$ of $\mathbf{h}$ and $\mathbf{R}_{cp}$ denotes the CP discarding matrix of size $N \times (N+K)$ defined as

$$\mathbf{R}_{cp} = \begin{bmatrix} \mathbf{O}_{N \times K} & \mathbf{I}_{N \times N} \end{bmatrix}_{N \times (N+K)} \quad (6)$$

And $\mathbf{n}(n) = \mathbf{R}_{cp} \mathbf{n}'(n)$. Based on the CP insertion and discarding, the channel matrix $\mathbf{H}$ can be represented by a circulant matrix $\mathbf{H}_c$ of size $N \times N$, i.e.,

$$\mathbf{H}_c = \mathbf{R}_{cp} \mathbf{H} \mathbf{T}_{cp} = \mathbf{F}^H \mathbf{\Lambda} \mathbf{F} \quad (7)$$

where $\mathbf{\Lambda}$ is the channel frequency response, and $\mathbf{F}$ is defined as a discrete Fourier transform (DFT) matrix. The received signal block $\mathbf{Y}$ after DFT can be written as

$$\mathbf{Y}(n) = \mathbf{F} \mathbf{y}(n) = \mathbf{\Lambda} \mathbf{F} \mathbf{x}(n) + \mathbf{F} \mathbf{n}(n) \quad (8)$$

Finally, after the frequency domain equalizer $\mathbf{W}$ and IDFT processing, we can get the detected signal $\hat{\mathbf{x}}(n)$

$$\hat{\mathbf{x}}(n) = \mathbf{F}^H \mathbf{W} \mathbf{Y}(n) = \mathbf{F}^H \mathbf{W} \mathbf{\Lambda} \mathbf{F} \mathbf{x}(n) + \mathbf{F}^H \mathbf{W} \mathbf{F} \mathbf{n}(n) \quad (9)$$

where $(\cdot)^H$ stands for the conjugate transpose. The equalizer $\mathbf{W}$ consists of ZF and MMSE equalizers.

(1). Zero Forcing (ZF)

$$\mathbf{W} = \mathbf{W}_{ZF} = \mathbf{\Lambda}^{-1} \quad (10)$$

(2). Minimum Mean Square Error (MMSE)

$$\mathbf{W} = \mathbf{W}_{MMSE} = \left(\mathbf{\Lambda}^H \mathbf{\Lambda} + \sigma_n^2 / \sigma_x^2 \mathbf{I}_{N \times N} \right)^{-1} \mathbf{\Lambda}^H \quad (11)$$

where σ_n^2 and σ_x^2 are the variance of noise and signal.

Substituting (7) and (11) into (9), the detected signal can be written as

$$\begin{aligned} \hat{\mathbf{x}}(n) &= \mathbf{F}^H \mathbf{W}_{MMSE} \mathbf{F} \mathbf{y}(n) \\ &= \mathbf{F}^H \mathbf{W}_{MMSE} \mathbf{F} \mathbf{H}_c \mathbf{x}(n) + \mathbf{F}^H \mathbf{W}_{MMSE} \mathbf{F} \mathbf{n}(n) \quad (12) \\ &= \bar{\mathbf{H}} \mathbf{x}(n) + \mathbf{F}^H \mathbf{W}_{MMSE} \mathbf{F} \mathbf{n}(n) \end{aligned}$$

where $\bar{\mathbf{H}} = \mathbf{F}^H \mathbf{W}_{MMSE} \mathbf{F} \mathbf{H}_c$, and $\bar{\mathbf{H}}$ is a new channel matrix of size $N \times N$. From figure 2, the energy of $\bar{\mathbf{H}}$ is concentrated on the diagonal, but there still have residue ICI in other subcarriers, which will degrade the system performance. So some interference cancellation systems are proposed to cancel the ICI and achieve better performance.

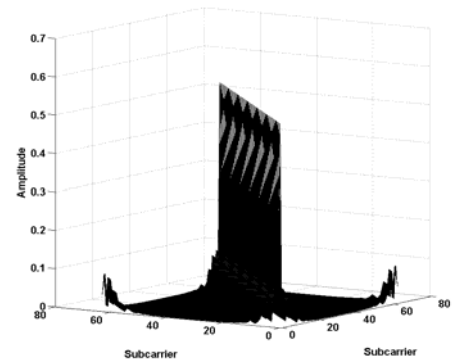


Figure 2. The characteristics of frequency domain channel matrix.

B. Frequency-Domain Decision Feedback Equalizer

(1) Iterative MMSE decision feedback equalizer

Figure 3 shows a block diagram of FD-DFE system, suppose that $(x_0, x_1, \dots, x_{N-1})$ is a symbol block and $(y_0, y_1, \dots, y_{N-1})$ is the corresponding received signal block. The received block is fed to the DFT operator, whose output

block is denoted $(Y_0, Y_1, \dots, Y_{N-1})$. The equalizer multiplies this signal block with its feedforward coefficients $(F_0, F_1, \dots, F_{N-1})$, and the resulting signal block enters an inverse DFT, which yields the output block $(\hat{x}_0, \hat{x}_1, \dots, \hat{x}_{N-1})$ on which the threshold detector bases its first decisions for the transmitted signal block.

Once the receiver makes a first set of decisions, the decision block is fed to a feedback filter with coefficients $(B_0, B_1, \dots, B_{N-1})$, and an iterative DFE is implemented. At the k th iteration, the feedforward and feedback filter block supplies

$$R_n(k) = F_n(k)Y_n + B_n(k)D_n(k-1), \quad n = 0, 1, \dots, N-1 \quad (13)$$

where the $F_n(k)$ and $B_n(k)$ coefficient sets are respectively the feedforward and feedback filter coefficients at the k th iteration, and the $D_n(k-1)$ are the frequency-domain decisions at the previous iteration.

The initial MMSE equalizer is given as

$$F_n(0) = \frac{\Lambda_n^*}{\sigma_n^2 / \sigma_x^2 + |\Lambda_n|^2}, \quad n = 0, 1, \dots, N-1 \quad (14)$$

where Λ_n is channel frequency response, σ_n^2 and σ_x^2 are the additive noise power and the power of the transmitted symbols respectively, and initial feedback filter coefficient is given as

$$B_n(0) = 0 \quad (15)$$

The first equalizer decisions are obtained using $\alpha_0 = 1$, and the definition of α_k is given in [3]

$$\alpha_k = 1 - \sqrt{k} / {}^{10}\sqrt{K} \quad (16)$$

where K is the number of iterations, At the k th iteration, the feedforward and the feedback filter coefficients are respectively given by

$$F_n(k) = \frac{\Lambda_n^*}{\sigma_n^2 / \sigma_x^2 + (1 - \alpha_{k-1}^2) |\Lambda_n|^2} \quad (17)$$

and

$$B_n(k) = \alpha_{k-1} \left[\Lambda_n F_n(k) - \frac{1}{N} \sum_{n=1}^N \Lambda_n F_n(k) \right], n = 0, 1, \dots, N-1 \quad (18)$$

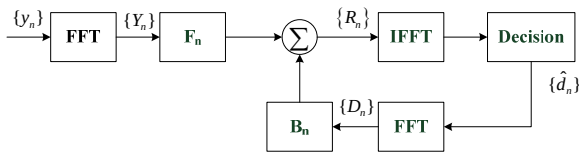


Figure 3. Block diagram of iterative frequency domain decision feedback equalizer.

(2) Iterative MF based decision feedback equalizer

In the iterative DFE proposed in [4], the feedforward filter is a matched filter (MF) at the final iteration. The idea is to maximize the SNR by the feedforward filter, and then to restore the ideal channel frequency response by the feedback filter. Obviously, the MF cannot be used as the feedforward filter until a set of decisions is available, because it increases ISI, and compensation of this requires a feedback filter.

Therefore, the feedforward filter in that DFE shifts linearly from a linear MMSE filter at the first pass to the MF at the last iteration.

At the k th iteration, the feedforward and the feedback filter coefficients are respectively given by

$$F_n(k) = \alpha_k \frac{\Lambda_n^*}{\sigma_n^2 / \sigma_x^2 + |\Lambda_n|^2} + (1 - \alpha_k) \Lambda_n^* \quad (19)$$

and

$$B_n(k) = 1 - F_n(k) \Lambda_n \quad (20)$$

The first equalizer decisions are obtained using $\alpha_0 = 1$, i.e., the equalizer is clearly a linear MMSE equalizer. Then, the α_k parameter decreases linearly as

$$\alpha_k = 1 - k / K \quad (21)$$

where K is the number of iterations. At the last iteration, $\alpha_K = 0$, and the feedforward filter is a matched filter.

$$F_n(K) = \Lambda_n^* \quad (22)$$

And (20) becomes

$$B_n(K) = 1 - |\Lambda_n|^2 \quad (23)$$

III. PARALLEL INTERFERENCE CANCELLATION

The residue ICI in other subcarriers will degrade the system performance. Thus, in this section, the PIC is used to cancel the ICI problems in SCBT system.

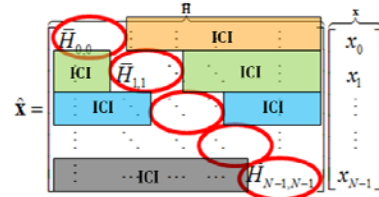


Figure 4. Schematic diagram of subcarrier interference.

A. Parallel Interference Cancellation

$\hat{\mathbf{x}}(n) = \bar{\mathbf{H}}\mathbf{x}(n)$ is defined in (12), and Figure 4 is the schematic diagram of subcarriers interference, the colored boxes are subcarrier interference. $\bar{H}_{i,d}$ is expressed as the d th data subcarrier to the i th interference subcarrier. When i is different from d , i.e., $i \neq d$, $\bar{H}_{i,d}\mathbf{x}(n)$ is the ICI term. Figure 5 is the block diagram of PIC in SCBT system. And $\tilde{\mathbf{x}}_n$ is the signal after canceling the ICI, which can be given as

$$\tilde{\mathbf{x}}_n = (\hat{\mathbf{x}}_n - (\bar{\mathbf{H}}_n - \mathbf{h}_n)(\tilde{\mathbf{d}} - \tilde{\mathbf{d}}_n))\bar{\mathbf{H}}_{n,n}^{-1}, \quad n = 0, \dots, N-1 \quad (24)$$

where $\bar{\mathbf{H}}_n$ is the $(n+1)$ th column vector of $\bar{\mathbf{H}}$, and $\mathbf{h}_n$ is defined as

$$\mathbf{h}_n = [\mathbf{0}_{1 \times n} \quad \bar{\mathbf{H}}_{n,n} \quad \mathbf{0}_{1 \times (N-n-1)}] \quad (25)$$

$\tilde{\mathbf{d}}$ is the modulated signal of QPSK after the decision

$$\tilde{\mathbf{d}} = [\tilde{d}_0 \quad \tilde{d}_1 \quad \dots \quad \tilde{d}_{N-1}]^T \quad (26)$$

and $\tilde{\mathbf{d}}_n$ is defined as

$$\tilde{\mathbf{d}}_n = \begin{bmatrix} \mathbf{0}_{n \times 1} \\ \tilde{\mathbf{d}}_n \\ \mathbf{0}_{(N-n-1) \times 1} \end{bmatrix} \quad (27)$$

After canceling the ICI terms, the cancelled signal $\tilde{\mathbf{x}}$ can be detected by the decision operation.

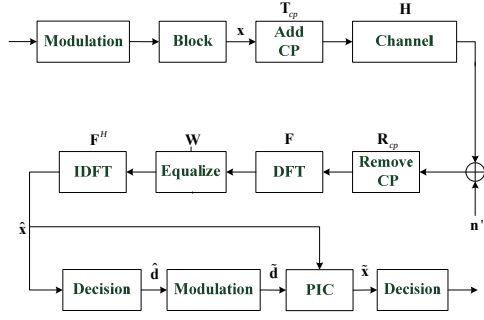


Figure 5. Block diagram of PIC in SCBT system.

B. PIC with Maximum Ratio Combining

PIC algorithm can overcome the ICI problem effectively and improve the BER performance obviously. However, as shown in (24) for only one-tap equalizer, it will result in the loss of energy for the symbol detection. Besides, in order to enhance the receiver performance in part III.A, the number of iterations needs to be increased. It will induce more computation complexity. Therefore, in order to alleviate the above problem, the PIC with maximum ratio combining technique is proposed in this paper. That is, with the aid of MRC scheme, the proposed PIC technique can effectively perform the interference cancellation and acquire the benefit of frequency diversity gain. In fact, with more taps for weighting combination, it will lead to higher frequency diversity gain. Furthermore, it indicates that the proposed technique can achieve better BER due to the diversity gain. This can mainly be attributed to the ability of this scheme to effectively deal with interference effects and achieve inherent frequency diversity with MRC.

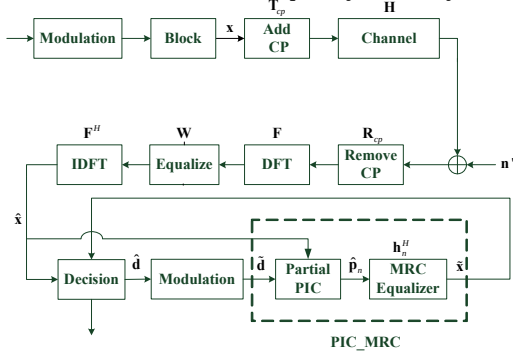


Figure 6. Block diagram of iterative PIC-MRC in SCBT system.

The block diagram is show in Figure 6. Its structure is very similar to PIC. The main difference is that PIC-MRC doing partial PIC first, and then combines all the subcarriers energy which including x_n , $n=0,1,\dots,N-1$ by MRC algorithm. Finally, using the MRC equalizer can obtain the detective signal. To simplify the exposition, we consider a simple case. First, from (12), we do the partial PIC to obtain $\hat{\mathbf{p}}_0$, and cancel all the

interference terms which do not include x_0 :

$$\begin{aligned} \hat{\mathbf{p}}_0 &= \begin{bmatrix} \hat{x}_0 \\ \hat{x}_1 \\ \vdots \\ \hat{x}_{N-1} \end{bmatrix} - \begin{bmatrix} 0 & \bar{H}_{0,1} & \cdots & \bar{H}_{0,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \bar{H}_{N-1,1} & \cdots & \bar{H}_{N-1,N-1} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_{N-1} \end{bmatrix} \\ &= \begin{bmatrix} \hat{x}_0 \\ \hat{x}_1 \\ \vdots \\ \hat{x}_{N-1} \end{bmatrix} - \begin{bmatrix} H_{0,1}x_1 + \cdots + H_{0,N-1}x_{N-1} \\ H_{1,1}x_1 + \cdots + H_{1,N-1}x_{N-1} \\ \vdots \\ H_{N-1,1}x_1 + \cdots + H_{N-1,N-1}x_{N-1} \end{bmatrix} \\ &= \hat{\mathbf{x}} - (\bar{\mathbf{H}} - \bar{\mathbf{H}}_0)\mathbf{x} \end{aligned} \quad (28)$$

where $\bar{\mathbf{H}}_0 = [\mathbf{h}_0 \quad \mathbf{0}_{N \times (N-1)}]$, and $\mathbf{h}_0$ is the first row vector of $\bar{\mathbf{H}}$. After MRC operation, the detective signal can be obtained by the MRC equalization

$$\begin{aligned} \tilde{x}_0 &= \mathbf{h}_0^H (\hat{\mathbf{x}} - (\bar{\mathbf{H}} - \bar{\mathbf{H}}_0)\mathbf{x}) \\ &= \begin{bmatrix} \bar{H}_{0,0} \\ \bar{H}_{1,0} \\ \vdots \\ \bar{H}_{N-1,0} \end{bmatrix}^H \begin{bmatrix} \hat{x}_0 \\ \hat{x}_1 \\ \vdots \\ \hat{x}_{N-1} \end{bmatrix} - \begin{bmatrix} 0 & \bar{H}_{0,1} & \cdots & \bar{H}_{0,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \bar{H}_{N-1,1} & \cdots & \bar{H}_{N-1,N-1} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_{N-1} \end{bmatrix} \end{aligned} \quad (29)$$

Similarly to the procedures of (28) and (29), the n th PIC-MRC signal can be obtained by

$$\tilde{x}_n = \mathbf{h}_n^H (\hat{\mathbf{x}} - (\bar{\mathbf{H}} - \bar{\mathbf{H}}_n)\mathbf{x}) \quad (30)$$

where

$$\bar{\mathbf{H}}_n = [\mathbf{0}_{N \times (n)} \quad \mathbf{h}_n \quad \mathbf{0}_{N \times (N-n-1)}] \quad (31)$$

$\mathbf{h}_n$ is the $(n+1)$ th row vector of $\bar{\mathbf{H}}$. PIC-MRC algorithm not only can acquire frequency diversity gain, but also reduce the computation complexity than PIC, which should need more iteration loops to enhance performance.

IV. COMPUTER SIMULATIONS

In this section, simulation results are conducted to demonstrate the performance of the proposed PIC-MRC system, and Table 1 is the system parameter settings. All the simulations are assuming perfectly known the channel state information.

Table 1: System simulated parameter

Parameter	Specification
Modulation type	QPSK
Subcarriers number	64
Multipath number	6
Channel model	Equal Gain Fading Channel
CP length	16

Figure 7 shows the BER performance of iterative MMSE decision feedback equalizer and iterative MF based decision feedback equalizer. The number of iteration is 2, 4, and 6 times. As shown in Figure 7, the system performance is better as the number of iteration increases. Besides, for the iteration number being 2, the performance of the iterative MMSE FDE can approach to the MMSE equalizer. At the iteration number

being 4 and 6, the performance of the iterative MMSE FDE increases about 1dB and 1.5dB than MMSE equalizer at $BER=4 \times 10^{-5}$, respectively. When the number of iteration is 6, the performance of iterative MMSE DFE is better than the iterative MF based DFE receiver about 1.4dB at $BER=2 \times 10^{-5}$. From [3], when the iteration number is up to 6 times, the iterative MF based DFE receiver losses the effect of compensating the causal interference which is the reason of the performance degradation.

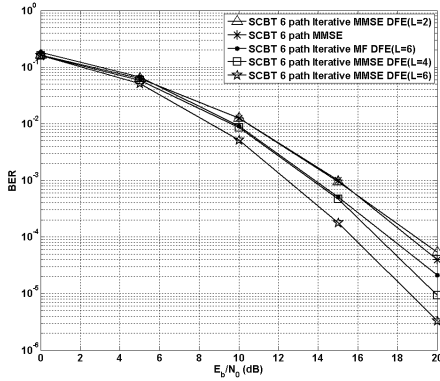


Figure 7. BER performance of iterative MMSE/MF based decision feedback equalizer.

Finally, Figure 8 shows the BER performance of PIC and PIC-MRC in SCBT system. The dotted lines are the best performance bound of PIC and PIC-MRC respectively. We can see that the performance of PIC-MRC is better about 1dB at $BER=10^{-5}$, but the performance is lower than iterative MMSE DFE ($K=6$) about 0.6dB. Therefore, the multiple iterations are used in the PIC-MRC system. As shown in Figure 9, after more iteration, the performance of PIC-MRC has increased obviously. After one iteration, the performance has been better than iterative MMSE DFE system 0.6dB at $BER=4 \times 10^{-6}$, and then the performance increases again about 0.2dB after 2 iterations. From above simulation results, the proposed iterative PIC-MRC in SCBT system can actually acquire better BER performance and involve low complexity.

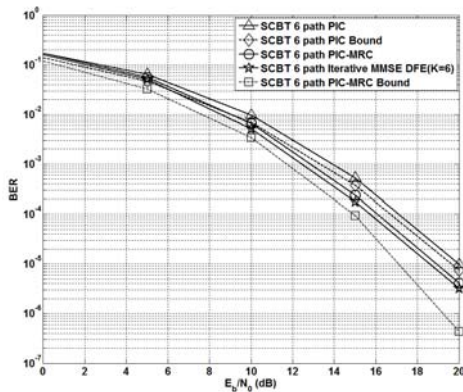


Figure 8. BER performance of PIC and PIC-MRC in SCBT system.

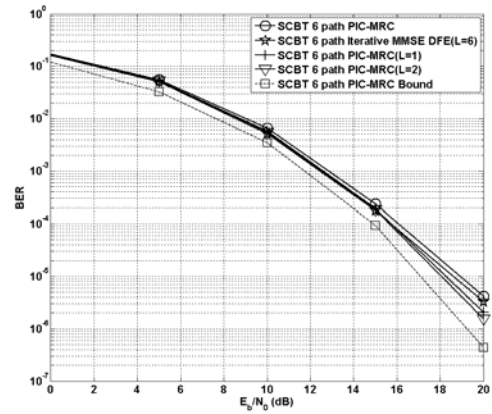


Figure 9. BER performance of iterative PIC-MRC in SCBT system.

V. CONCLUSIONS

The PIC-MRC system is proposed for SCBT system, which is in order to achieve better BER performance and low complexity at the receiver side. With the aid of MRC scheme, the proposed PIC technique can effectively perform the interference cancellation and acquire the benefit of frequency diversity gain, which can achieve better BER performance. Simulation results reveal that the proposed low complexity PIC-MRC system can provide robust performance and outperform the conventional PIC and the iterative FD-DFE systems over multipath fading channel environment.

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