社団法人 電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
TECHNICAL REPORT OF IEICE

Effect of Gaussian Channel Estimation Error on IBI Cancellation and Circular Property Loss Restoration for Broadband DS-CDMA Combining FDE Without CP Insertion

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***Abstract*-In broadband DS-CDMA uplink transmission using frequency-domain equalization (FDE) without cyclic prefix (CP) insertion, the transmission performance degrades due to inter block interference (IBI) and circular property loss. The schemes were proposed to solve the problems of IBI and circular property loss in our previous study with the assumption of perfect channel estimation. In this paper, the Gaussian error channel model is used and the effect of estimating accuracy on the bit error rate (BER) is discussed. The requirement for practical channel estimation is also given based on the result.**

***Keywords*- DS-CDMA, MMSE-FDE, IBI cancellation, Circular property loss restoration, Gaussian error**

I. INTRODUCTION

In broadband direct sequence code division multiple access (DS-CDMA), one way to achieve the high-speed data transmission is to use orthogonal multi-code multiplexing [1]. However the wireless channel becomes very frequency selective [2] due to the multipath delay and as a result, the bit error rate (BER) performance of multi-code DS-CDMA degrades severely due to the frequency selective fading. An effective technique to improve the BER performance is the RAKE combining. However, as the chip rate increases, the frequency selectivity of the multipath channel becomes more severe due to the increasing number of resolvable paths. Therefore, minimum mean square error (MMSE) frequency domain equalization (FDE) [3] has been applied at the receiver instead of RAKE combining. It is proved [4] that MMSE-FDE outperforms RAKE combining.

Broadband DS-CDMA uplink transmission using FDE is a block transmission [5]. To avoid the inter block interference (IBI) [6], the cyclic prefix (CP) length must be longer than the maximum channel time delay. However, the insertion of CP decreases the bandwidth efficiency. Therefore, block transmission without CP has been considered to improve the bandwidth efficiency. The absence of CP produces IBI and the circular property loss. The schemes to solve the problems of IBI and circular property loss were proposed in our previous study with the assumption of perfect channel estimation. The results showed that circular property loss restoration is more powerful that IBI cancellation to improve the bit error rate (BER) performance. However, perfect channel estimation is impossible and channel estimation error occurs in practical system. In this paper, the channel estimation with Gaussian error is assumed. The effect of the estimating accuracy on the BER is discussed.

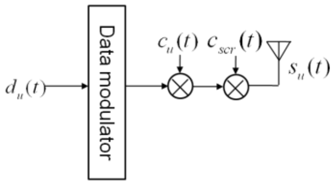
The rest of this paper is organized as follows. Section II presents the system model of broadband DS-CDMA uplink transmission using FDE without CP. The impact of IBI and circular property loss on the bit error rate (BER) performance is discussed. In Section III, IBI cancellation and circular property loss restoration are described. In Section IV, the channel estimation with Gaussian error is modeled. The effect of the accuracy of channel estimation on BER performance is evaluated by computer simulation in Section V. Finally the paper will be concluded in Section VI.

II. SYSTEM MODEL

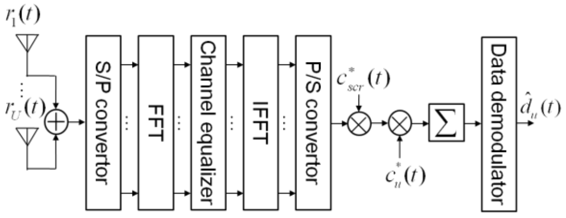
In this study, DS-CDMA uplink transmission [7] is used and the system model is described in Section A. The reason of IBI and circular property loss is explained in Section B.

A. DS-CDMA uplink transmission

Figure 1 shows the system model of multi-code DS-CDMA transmission. At the transmitter side, after data modulation for the u -th ($u=0\sim U-1$) data stream $d_u\left(t\right)$, the binary information sequence is spread by orthogonal spreading code $c_u\left(t\right)$ of spreading factor SF ($SF>U$). Then the sequence is multiplied by a scrambling sequence $c_{scr}\left(t\right)$ to generate the multi-code DS-CDMA data stream. At the receiver side, the signal is descrambled and de-spread after equalization. And the U parallel symbol streams are converted back to a sequence by a parallel/serial (P/S) converter before demodulation.



(a). Transmitter



(b). Receiver

Fig.1 System model of the multi-code DS-CDMA

The multi-code DS-CDMA signal to be transmitted is expressed as

$$s(t)=\sqrt{\frac{2E_c}{T_c}}\sum_{u=0}^{U-1}d_u\left(\left\lfloor\frac{t}{SF}\right\rfloor\right)c_{scr}\left(t\right)c_u\left(t\bmod SF\right), \tag{1}$$

where E_c and T_c denote the chip energy and chip duration, respectively; SF is the spreading factor, u is the user index; d_u is the data sequence of user u; $c_{scr}\left(t\right)$ is the channel-specific scrambling code; $c_u\left(t\right)$ is the user-specific spreading code; $\lfloor x\rfloor$ represents the largest integer less than or equal to x. The transmitted DS-CDMA signal propagates through a multi-path channel. At the receiver side, the base band equivalent received signal is given by

$$r(t)=\sum_{l=0}^{L-1}h_l s(t-\tau_l)+\eta(t), \tag{2}$$

where h_l is the l-th complex-valued path gain satisfying $\sum_{l=0}^{L-1}E[|h_l|^2]=1$ ($E[\bullet]$ denotes the ensemble average operation). In this study, integer chip-spaced multi-path delay is used and $\tau_l=l$. $\eta\left(t\right)$ is a zero-mean complex-valued additive white Gaussian noise (AWGN) with a variance of $2N_0/T_c$, where N_0 is the single-side noise power spectrum density.

B. Inter-block interference and circular property loss

Figure 2 shows the effect of multi-path fading on the received signal. Suppose that data block $\#M$ is under detection. Due to the multi-path delay, data block $\#M-1$ will "overlap" with data block $\#M$. On the other hand, the circular property is lost due to the absence of received CP replica. In order to detect block $\#M$, IBI should be removed and the circular property must be restored so that MMSE-FDE algorithm can be applied to the received block signal.

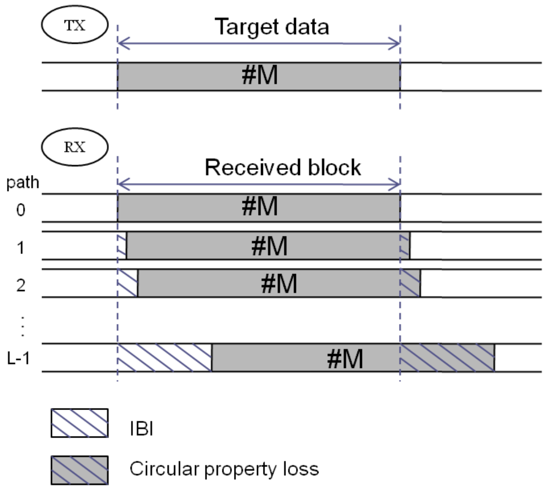


Fig.2 IBI and Circular property loss

III. PRINCIPLE OF IBI CANCELLATION AND CIRCULAR PROPERTY LOSS RESTORATION

The steps of the proposed MMSE FDE receiver with IBI cancellation and circular property loss restoration are shown in Figure 3. At first, the IBI will be cancelled using the data decision of the previous block; then imperfect circular property loss restoration will be performed; in the next MMSE FDE will be applied to the data block after IBI cancellation and imperfect circular property loss restoration, an improved circular property loss restoration can then be carried out by using the data decision after MMSE FDE. The performance of block detection can be improved in an iterative way until the termination condition is satisfied.

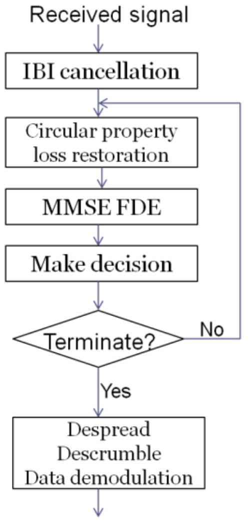


Fig. 3 Flow at receiver side

At the receiver side, the received DS-CDMA signal stream is divided into a sequence of N_c-chip blocks. The signal vector can be expressed using matrix form as

$$\begin{aligned}\mathbf{r}&=\mathbf{h}\mathbf{s}_0+\mathbf{v}+\boldsymbol{\eta}\\&=\mathbf{h}\mathbf{s}_0+\mathbf{h}_{-1}\left(\mathbf{s}_{-1}-\mathbf{s}_0\right)+\boldsymbol{\eta}\ .\\&=\mathbf{h}\mathbf{s}_0+\mathbf{h}_{-1}\mathbf{s}_{-1}-\mathbf{h}_{-1}\mathbf{s}_0+\boldsymbol{\eta}\end{aligned} \tag{3}$$

In the right hand side of the Equation (3), the first term contains the desired signal, the second term contains the IBI and the third term contains the power loss. $\mathbf{s}_0$, $\mathbf{s}_{-1}$ and $\boldsymbol{\eta}$ are respectively $N_c\times 1$ vectors given as

$$\begin{cases}\mathbf{s}_0=\left[s\left(0\right),s\left(1\right),\cdots,s\left(N_c-1\right)\right]^T\\ \mathbf{s}_{-1}=\left[s\left(-N_c\right),s\left(-N_c+1\right),\cdots,s\left(-1\right)\right]^T\ .\\ \boldsymbol{\eta}=\left[\eta\left(0\right),\eta\left(1\right),\cdots,\eta\left(N_c-1\right)\right]^T\end{cases} \tag{4}$$

$\mathbf{h}$ is the matrix of channel impulse response and $\mathbf{h}_{-1}$ is the matrix of channel impulse response to cause the interference. $\mathbf{h}_{-1}$ can be given as

$$\mathbf{h}_{-1}=\begin{bmatrix} & h_{L-1} & \cdots & h_1\\ & & \ddots & \vdots\\ & & & h_{L-1}\\ \mathbf{0} & & & \end{bmatrix}_{N_c\times N_c}, \tag{5}$$

where, h_l is the complex valued path gain of the l th path.

Before giving the expressions for $\mathbf{h}$, we should notice that, since there is no cyclic prefix, the circular property of $\mathbf{h}$ is lost. Therefore, the IBI cancellation and CPL restoration must be performed to recover the circular property. According to Equation(3),

$$\begin{cases} \mathbf{v}_{-1} = \mathbf{h}_{-1}\mathbf{s}_{-1} \\ \mathbf{v}_0 = \mathbf{h}_{-1}\mathbf{s}_0 \end{cases}, \tag{6}$$

where, $\mathbf{v}_{-1}$ is the IBI component, which should be cancelled; and $\mathbf{v}_0$ is the CPL component, which should be restored.

To solve these two problems, perfect IBI cancellation, perfect CPL restoration and imperfect restoration will be discussed and compared in the following.

A. Perfect IBI cancellation

To perform IBI cancellation, the estimation of the previous block $\#M-1$ is required. The IBI component is reconstructed based on Equation (6) and then subtracted from the target block $\#M$.

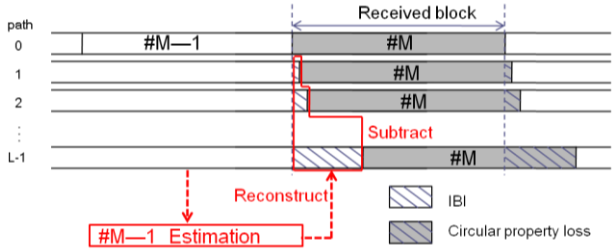


Fig. 4 Perfect IBI cancellation

To observe the effect of perfect IBI cancellation, $\mathbf{s}_{-1}$, which is the previous block signal, is assumed to be perfectly restored. The channel estimation is also assumed to be perfect. Therefore, the IBI component can be perfectly cancelled by using $\mathbf{h}_{-1}$ and $\mathbf{s}_{-1}$.

B. Perfect circular property loss restoration

It can be seen from Figure 5 that, to perform circular property loss restoration, the estimation for the target block $\#M$ is required. The power loss component is reconstructed based on Equation (6) and then added to the head of the target block $\#M$.

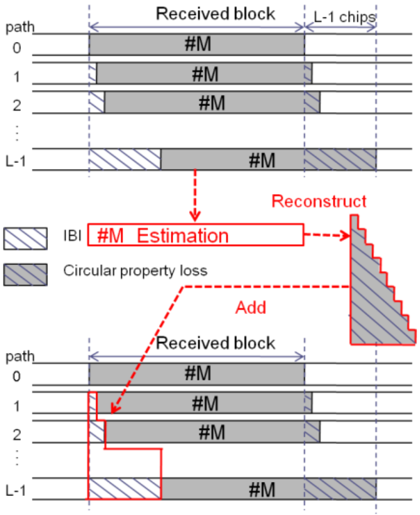


Fig. 5 Perfect circular property loss restoration

Similarly, perfect $\mathbf{s}_0$ and $\mathbf{h}_{-1}$ will be used to observe the effect of perfect circular property loss restoration.

C. Imperfect circular property loss restoration [8]

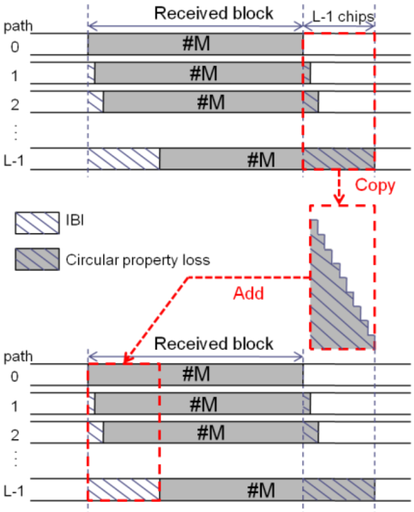


Fig. 6 Imperfect circular property loss restoration

Perfect $\mathbf{s}_0$ is used in Section B for perfect circular property loss. However, $\mathbf{s}_0$ is the target signal to be detected. In real case, it is unknown during the processing procedure. Therefore a scheme of imperfect circular property loss restoration is proposed, which will simply copy the head of the next block and add to the head of the target block, as shown in Figure 6.

After the IBI cancellation and CPL restoration, the circular property of the channel matrix $\mathbf{h}$ is recovered. The expression can be taken as a circular matrix,

$$\mathbf{h} = \begin{bmatrix} h_0 & & & h_{L-1} & \cdots & h_1 \\ \vdots & \ddots & & & \ddots & \vdots \\ h_{L-2} & \vdots & h_0 & \mathbf{0} & & h_{L-1} \\ h_{L-1} & \vdots & \vdots & h_0 & & \\ & \ddots & \vdots & \vdots & \ddots & \\ \mathbf{0} & & h_{L-1} & h_{L-2} & \cdots & h_0 \end{bmatrix}_{N_c \times N_c} . \tag{7}$$

Therefore, the received signal can be given as

$$\mathbf{r} = \mathbf{h}\mathbf{s}_0 + \boldsymbol{\eta}, \tag{8}$$

MMSE-FDE is performed after the interference cancellation. The FDE is to apply N_c-point fast Fourier transform (FFT) to the signals. Frequency domain components are then equalized by weight $\{W(k)\}, k = 0 \sim N_c - 1$, shown in Figure 7.

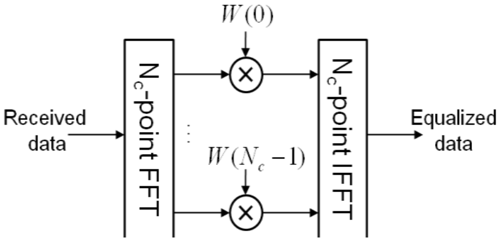


Fig.7 Frequency domain equalizer

By N_c-point FFT, the received signal $\mathbf{r}$ is transformed into the frequency domain signal $\mathbf{R}=\left[R(0),R(1),\cdots,R(N_c-1)\right]$, which can be given by

$$\mathbf{R}=\mathbf{F}\cdot\mathbf{r}=\mathbf{H}\left(\mathbf{F}\mathbf{s}_0\right)+\mathbf{F}\boldsymbol{\eta}, \tag{9}$$

where $\mathbf{H}=\mathbf{F}\mathbf{h}\mathbf{F}^H$, $\mathbf{F}$ is the $N_c\times N_c$ FFT matrix given as

$$\mathbf{F}=\frac{1}{\sqrt{N_c}}\begin{bmatrix}1 & 1 & \cdots & 1\\ 1 & e^{-j2\pi\frac{1\cdot 1}{N_c}} & \cdots & e^{-j2\pi\frac{1\cdot(N_c-1)}{N_c}}\\ \vdots & \vdots & \ddots & \vdots\\ 1 & e^{-j2\pi\frac{(N_c-1)\cdot 1}{N_c}} & \cdots & e^{-j2\pi\frac{(N_c-1)\cdot(N_c-1)}{N_c}}\end{bmatrix}_{N_c\times N_c}. \tag{10}$$

Since $\mathbf{h}$ is a circular matrix, $\mathbf{H}$ becomes a diagonal matrix denoted as

$$\mathbf{H}=diag\left[H(0),\cdots,H(k),\cdots,H(N_c-1)\right], \tag{11}$$

where

$$H(k)=\sum_{l=0}^{L-1}h_l\exp\left(-j2\pi k\frac{\tau_l}{N_c}\right). \tag{12}$$

Then MMSE-FDE is applied to $\mathbf{R}$ so that $\hat{\mathbf{R}}=\mathbf{W}\cdot\mathbf{R}$, where $\mathbf{W}$ is the MMSE-FDE weight matrix. $\hat{\mathbf{R}}$ is given as

$$\hat{\mathbf{R}}=\mathbf{W}\mathbf{H}\left(\mathbf{F}\mathbf{s}_0\right)+\mathbf{W}\mathbf{F}\boldsymbol{\eta}, \tag{13}$$

According to the Wiener theory, for the given $\mathbf{h}$, $\mathbf{W}$ can be obtained as

$$\mathbf{W}=\mathbf{H}^H\left\{\mathbf{H}\mathbf{H}^H+\left(U\frac{E_c}{N_0}\right)^{-1}\mathbf{I}\right\}^{-1}. \tag{14}$$

The right side of Equation (14) is a diagonal matrix, so $\mathbf{W}$ can also be expressed by a diagonal matrix as $\mathbf{W}=diag\left[W(0),\cdots,W(k),\cdots,W(N_c-1)\right]$, resulting in one-tap MMSE-FDE. $W(k)$ is given by

$$W(k)=\frac{H^*(k)}{\left|H(k)\right|^2+(U\frac{E_c}{N_0})^{-1}}, \tag{15}$$

The frequency-domain signal $\hat{\mathbf{R}}$ after MMSE-FDE is transformed by an N_c-point inverse FFT (IFFT) back to the time-domain signal block as $\hat{\mathbf{r}}=\mathbf{F}^H\hat{\mathbf{R}}$. $\hat{\mathbf{r}}$ can be expressed as

$$\hat{\mathbf{r}}=\left(\frac{1}{N_c}tr\left[\mathbf{W}\mathbf{H}\right]\right)\mathbf{s}_0+\hat{\boldsymbol{\mu}}+\hat{\boldsymbol{\eta}}, \tag{16}$$

where the first term is the desired signal and, $\hat{\boldsymbol{\mu}}$, $\hat{\boldsymbol{\eta}}$ are the residual inter-chip interference (ICI) and noise component, respectively. $\hat{\boldsymbol{\mu}}$ and $\hat{\boldsymbol{\eta}}$ can be expressed as

$$\begin{cases}\hat{\boldsymbol{\mu}}=\left\{\mathbf{F}^H\left(\mathbf{W}\mathbf{H}\right)\mathbf{F}-\left(\frac{1}{N_c}tr\left[\mathbf{W}\mathbf{H}\right]\right)\mathbf{I}\right\}\mathbf{s}_0\\ \hat{\boldsymbol{\eta}}=-\mathbf{F}^H\left(\mathbf{W}\mathbf{F}\right)\boldsymbol{\eta}\end{cases}. \tag{17}$$

Finally, the signal is despread, descrambled and decoded.

IV. CHANNEL MODEL

Channel estimation with Gaussian error is used to evaluate the effect of channel estimation accuracy on the IBI cancellation and circular property loss restoration.

The channel estimation of the impulse response series $\{h_l\}, l=0,1,...,L-1$ can be expressed as

$$\hat{h}_l=h_l+\Delta h_l, l=0,1,...,L-1. \tag{18}$$

where, Δh_l is a Gaussian random variable with zero mean and variance of σ_e^2, $\Delta h_l\sim N\left(0,\sigma_e^2\right)$.Frequency domain channel response $\hat{\mathbf{H}}$ is then given by

$$\hat{\mathbf{H}}=diag\left[\hat{H}(0),...,\hat{H}(k),...,\hat{H}(N_c-1)\right] \tag{19}$$

where

$$\hat{H}(k)=\sum_{l=0}^{L-1}\hat{h}_l\exp\left(-j2\pi k\frac{\tau_l}{N_c}\right). \tag{20}$$

V. SIMULATION RESULTS

A. Simulation parameters

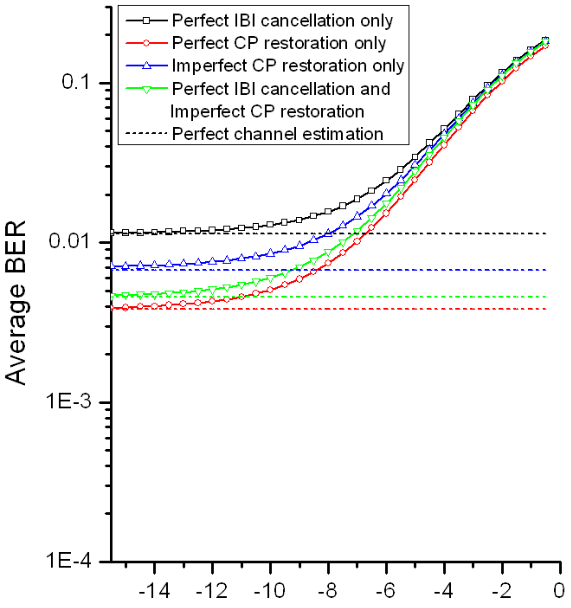
In this section, the performance of IBI cancellation and circular property loss restoration will be evaluated. The simulation parameters used are shown in Table 1. QPSK transmission is assumed and the propagation channel is assumed to be a frequency-selective block Rayleigh fading channel, which means the channel remains unchanged during a block. The channel has a chip-spaced 16-path uniform power profile. Ideal channel estimation is assumed. One user is considered and multi-user case, namely multi-user interference cancellation, will be considered in our future work. The normalized mean squared error (NMSE) which is normalized by the variance of channel impulse response is used as the measurement of Gaussian error. Therefore the NMSE equals to $\sigma_e^2 / \sigma^2 (dB)$, where σ^2 represents the variance of channel impulse response. NMSE varies within a range of [-16dB, 0dB].

Table 1 Simulation parameters

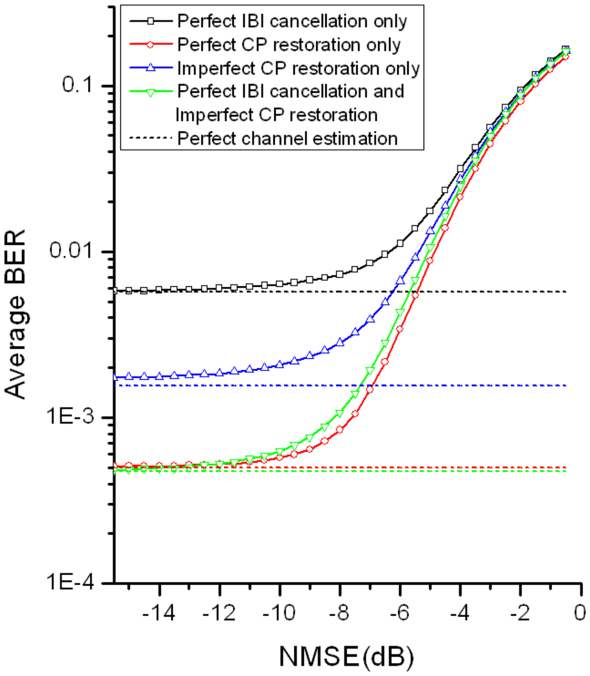
Transmitter	Data modulation	QPSK
	Spreading sequence	Product of Walsh sequence and Long PN sequence
	Spreading factor	SF=4
	Number of user	Single user
Channel model	Type	Frequency selective block Rayleigh fading
	Number of path	L=16-path
	Decay factor	0dB
	Delay time	Chip-spaced
Receiver	Equalization	MMSE FDE
	Channel estimation	Gaussian error
	FFT size	Nc=256

B. Average BER performance affected by Gaussian error

Figure 8 shows the effect of channel estimation error on the average BER performance with $E_b / N_0 = 10dB$ and $E_b / N_0 = 20dB$, respectively. The dashed lines are the results with perfect channel estimation. It can be observed that, in the region of higher channel estimation error ($NMSE \in [-4, 0](dB)$), generally the BER performance for all the proposed schemes becomes poor and converges eventually. And the performance of block detection is mainly dominated by the channel estimation error. As the accuracy of the estimation improves, the BER performance becomes better. The superiority of circular property loss restoration over the IBI cancellation can still be observed; and when imperfect circular property loss restoration is combined with perfect IBI cancellation, a similar performance to perfect cyclic property loss restoration can be achieved, which is also the same conclusion as the previous study. When the channel estimation becomes more accurate, e.g., $NMSE < -10(dB)$, the curves are very close to the perfect channel estimation performance, which shows the influence on the BER performance is nearly zero.



(a) E_b/N_0=10dB



(b) E_b/N_0=20dB

Fig.8 Average BER performance vs NMSE(dB)

It can be learnt from the results that the proposed schemes are sensitive to the channel estimation error. Taking 0.4dB BER performance degradation as an example, the corresponding Gaussian error NMSE (dB) for each scheme is listed in Table 2. From this table, it can be observed that perfect IBI cancellation has the best tolerance to the channel estimation error. While imperfect circular property loss restoration scheme exhibits the poorest robustness to the estimating error. Therefore, the practical channel estimation in the future work should satisfy the criteria to guarantee the performance of IBI cancellation and circular property loss restoration.

Table 2 NMSE (dB) of Gaussian Error (0.4dB degradation)

E_b/N_0 (dB)	Perfect IBI	Perfect CPL	Imperfect CPL	Perfect IBI+ Imperfect CPL
10	-10.5	-12.5	-13	-13
20	-10.5	-10.5	-16	-12.5

VI. CONCLUSION

In this paper, the MMSE-FDE receiver is considered for broadband DS-CDMA uplink transmission using FDE without CP insertion. The impact of Gaussian error channel on perfect IBI cancellation, perfect circular property loss and imperfect circular property loss has been discussed. It was shown that, in the region of higher channel estimation error, generally the BER performance for all the proposed schemes becomes poor and converges eventually. When the channel estimation becomes more accurate, the curves become close to the perfect channel estimation performance. And perfect IBI cancellation has the best tolerance to the channel estimation error. While imperfect circular property loss restoration scheme exhibits the poorest robustness to the estimating error.

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