Inter-chip Interference Cancellation for DS-CDMA with Frequency-domain Equalization

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Abstract*—The bit error rate (BER) performance of DS-CDMA in a frequency-selective fading channel can be significantly improved by the use of frequency-domain equalization (FDE). However, for a small spreading factor *SF*, the residual inter-chip-inference (ICI) degrades the BER performance. In this paper, we propose three types of ICI cancellation and the BER performance improvement is evaluated by computer simulation. The ICI replica is generated and subtracted from the FDE-equalized chip sequence. The reduction in E_b/N_0 for achieving a BER=10^{-4} is as much as about 4.2 dB when the spreading factor *SF*=4. Joint use of antenna diversity combining and ICI cancellation is also presented.

Keyword;* *DS-CDMA, Frequency-domain equalization, ICI cancellation

I. INTRODUCTION

Wireless channel is composed of many propagation paths with different time delays, producing frequency-selective multipath fading [1]. In a frequency-selective fading channel, the bit error rate (BER) performance of single-carrier (SC) transmission significantly degrades due to severe inter-symbol-interference (ISI). Direct-sequence code division multiple access (DS-CDMA) can exploit the channel frequency-selectivity by the use of coherent rake receiver that resolves the propagation paths having different time delays and coherently combines them to achieve the path diversity effect [2]. Wideband DS-CDMA has been adopted as a wireless access technique in the 3rd generation mobile communications systems, known as IMT-2000 systems, for data transmissions of up to a few Mbps [3]. However, in the case of broadband wireless data transmissions of more than a few Mbps using DS-CDMA, the transmission performance may significantly degrade due to strong inter-path interference (IPI) even if coherent rake combining is used.

Recently, multi-carrier (MC)-CDMA which attains the frequency diversity effect by one-tap frequency-domain equalization (FDE) has been attracting much attention for broadband wireless data transmissions in a severe frequency-selective channel [4~6]. However, MC-CDMA has the problem of large peak-to-average power ratio (PAPR). Recently, it was suggested [7] that minimum mean square error (MMSE)-FDE can be successfully applied to the DS-CDMA signal reception in order to improve its BER performance in a frequency-selective fading channel. It has been shown [8,9] that MMSE-FDE provides a better BER performance than coherent rake combining. However, for a small spreading factor *SF* (an extreme case is the nonspread SC system of *SF*=1), the inter-chip-inference (ICI) degrades the BER performance even if MMSE-FDE is applied. For the case of rake combining, many IPI cancellers have been proposed, e.g., [10]. In this paper, we propose three types of ICI cancellers for DS-CDMA with FDE. The BER performance improvement is evaluated by computer simulation.

Remainder of this paper is organized as follows. Section 2 presents the transmission system model for DS-CDMA with MMSE-FDE. In Section 3, three types of ICI cancellers based on MMSE and maximum ratio combining (MRC)-FDE are proposed. In Section 4, the achievable BER performance in a frequency-selective Rayleigh fading channel is evaluated by computer simulation. The effect of ICI cancellers is discussed. Section 5 offers some conclusions.

II. DS-CDMA WITH JOINT FDE AND ICI CANCELLATION

A. *Overall transmission system model*

Transmission system model for DS-CDMA with joint FDE and antenna diversity combining is illustrated in Fig.1. At the transmitter, the binary data sequence is transformed into the data modulated symbol sequence $\{d(n)\}$ and then spread by multiplying with the spreading sequence $\{c(t)\}$ having a spreading factor of *SF*. Note that an extreme case is the nonspread SC system with *SF*=1. After chip interleaving, the chip sequence is divided into a sequence of blocks of N_c chips each and then, the last N_g chips of each block is copied as a cyclic prefix and inserted into the guard interval (GI) at the beginning of each block to form a sequence of frames of N_c+N_g chips each.

The GI-inserted chip sequence is transmitted over a frequency-selective fading channel and is received by N_r diversity antennas at the receiver. After the removal of GI, the received chip sequence on each antenna is decomposed by N_c-point FFT into N_c subcarrier components (the terminology "subcarrier" is used for explanation purpose only although subcarrier modulation is not used). Then, joint FDE and antenna diversity combining is carried out. Finally, inverse FFT (IFFT) is applied to obtain the equalized and diversity combined time-domain chip sequence for chip de-interleaving, despreading and data demodulation.

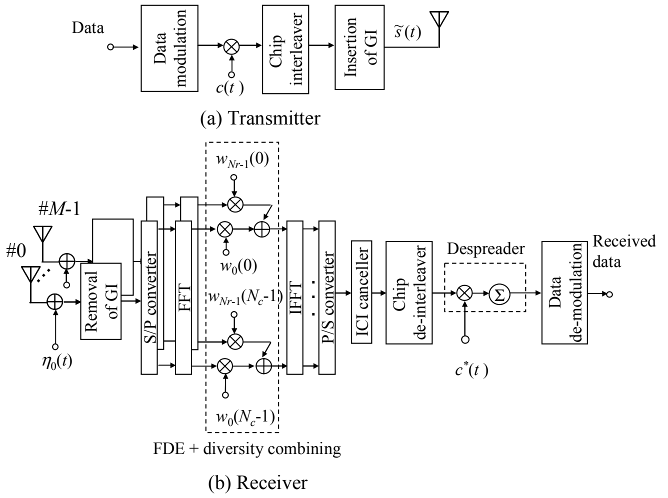


Figure 1. Transmission system model for DS-CDMA with joint FDE and ICI canceller.

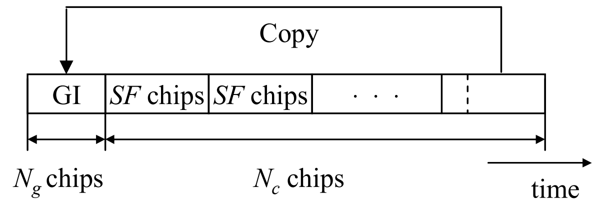


Figure 2. Frame structure.

B. Received signal

Throughout this paper, chip-spaced time representation of transmitted signals is used. Without loss of generality, the data symbol sequence $\{d(n); n=0\sim N_c/SF-1\}$ and the spreading chip sequence $\{c(t); t=0\sim N_c-1\}$ of one frame length are considered, where N_c and SF are chosen so that the value of N_c/SF becomes an integer. After chip interleaving and GI insertion, the GI-inserted chip sequence $\{\tilde{s}(t); t=-N_g\sim N_c-1\}$ can be represented, using the equivalent lowpass representation, as

$$\tilde{s}(t)=\sqrt{2E_c/T_c}\,s(t \bmod N_c) \quad ,(1)$$

where E_c and T_c denote the chip energy and the chip duration, respectively, and $\{s(t); t=0\sim N_c-1\}$ is given by

$$s(t)=d(\lfloor t/SF \rfloor)c(t) \quad ,(2)$$

where $\lfloor x \rfloor$ represents the largest integer smaller than or equal to x.

The propagation channel is assumed to be a frequency-selective fading channel having L discrete paths, each subjected to independent fading, where the time delay of the lth path ($l=0\sim L-1$) is assumed to be τ_l. The discrete-time impulse response $h_m(t)$ of multipath channel observed by the mth receive antenna can be expressed as

$$h_m(t)=\sum_{l=0}^{L-1}\xi_{m,l}\delta(t-\tau_l) \quad ,(3)$$

where $\xi_{m,l}$ is the l-th path complex gain experienced at the mth antenna with $\sum_{l=0}^{L-1}E[|\xi_{m,l}|^2]=1$ (E[.] denotes the ensemble average operation). In this paper, we assume block fading, where the path gains stay constant over one frame duration. The chip sequence $\{r_m(t); m=0\sim N_r-1, t=-N_g\sim N_c-1\}$ received on the mth antenna can be represented as

$$r_m(t)=\sum_{l=0}^{L-1}\xi_{m,l}\tilde{s}(t-\tau_l)+\eta_m(t) \quad ,(4)$$

where $\eta_m(t)$ is the complex Gaussian process with zero-mean and a variance of $2N_0/T_c$ with N_0 being the single-sided power spectrum density of the additive white Gaussian noise (AWGN) process.

C. Joint FDE and antenna diversity combining

After the removal of GI from the received chip sequence $\{r_m(t)\}$, N_c-point FFT is applied to decompose $\{r_m(t)\}$ into N_c subcarrier components $\{R_m(k); k=0\sim N_c-1\}$. The kth subcarrier component $R_m(k)$ can be written as

$$R_m(k)=\sqrt{2E_c/T_c}\,H_m(k)S(k)+\Pi_m(k) \quad ,(5)$$

where $S(k)$, $H_m(k)$ and $\Pi_m(k)$ are the kth subcarrier components of the N_c-chip signal sequence $\{s(t); t=0\sim N_c-1\}$, the channel gain and noise component due to the AWGN, respectively. They are given by

$$\begin{cases} S(k)=\sum_{t=0}^{N_c-1}s(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \\ H_m(k)=\sum_{l=0}^{L-1}\xi_{m,l}\exp\left(-j2\pi k\frac{\tau_l}{N_c}\right) \\ \Pi_m(k)=\sum_{t=0}^{N_c-1}\eta_m(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \end{cases} \quad (6)$$

Then, joint one-tap FDE and antenna diversity combining is carried out to obtain

$$\begin{aligned}\hat{R}(k)&=\sum_{m=0}^{N_r-1}R_m(k)w_m(k) \\ &=\sqrt{2E_c/T_c}\,S(k)\hat{H}(k)+\hat{\Pi}(k)\end{aligned} \quad ,(7)$$

where $w_m(k)$ is the equalization weight and $\hat{H}(k)$ and $\hat{\Pi}(k)$ are the equivalent channel gain and the noise component after joint FDE and antenna diversity combining, respectively, and are given by

$$\begin{cases} \hat{H}(k) = \sum_{m=0}^{N_r-1} w_m(k) H_m(k) \\ \hat{\Pi}(k) = \sum_{m=0}^{N_r-1} w_m(k) \Pi_m(k) \end{cases} .(8)$$

We consider MMSE- and MRC-FDE. They are given by

$$w_m(k) = \begin{cases} \dfrac{H_m^*(k)}{\sum_{m=0}^{N_r-1} |H_m(k)|^2 + (E_c/N_0)^{-1}}, & \text{MMSE - FDE} \\ H_m^*(k), & \text{MRC - FDE} \end{cases} ,(9)$$

where E_c/N_0 is the average chip energy-to-AWGN power spectrum density ratio and * denotes complex conjugation. The MRC weight maximizes the signal-to-noise ratio (SNR) at each subcarrier. The MMSE weight is chosen so that the mean square error (MSE) between $S(k)$ and $\hat{R}(k)$ is minimized.

N_c-point IFFT is applied to $\{\hat{R}(k); k = 0 \sim N_c - 1\}$ to obtain the time-domain chip sequence of $\{\hat{r}(t); t = 0 \sim N_c - 1\}$:

$$\hat{r}(t) = \sqrt{\frac{2E_c}{T_c}} \left(\frac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{H}(k) \right) s(t) + \mu(t) + \hat{\eta}(t) \quad ,(10)$$

where the first term represents the transmitted chip sequence, the second is the ICI component and the third is the noise component. $\mu(t)$ and $\hat{\eta}(t)$ can be represented as

$$\begin{cases} \mu(t) = \sqrt{\dfrac{2E_c}{T_c}} \dfrac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{H}(k) \left[\sum_{\substack{\tau=0 \\ \neq t}}^{N_c-1} s(\tau) \exp\left(j2\pi k \dfrac{t-\tau}{N_c} \right) \right] \\ \hat{\eta}(t) = \dfrac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{\Pi}(k) \exp\left(j2\pi k \dfrac{t}{N_c} \right) \end{cases} .(11)$$

Finally, despreading is carried out on $\{\hat{r}(t)\}$, giving

$$\hat{d}(n) = \frac{1}{SF} \sum_{t=nSF}^{(n+1)SF-1} \hat{r}(t) c^*(t) \quad ,(12)$$

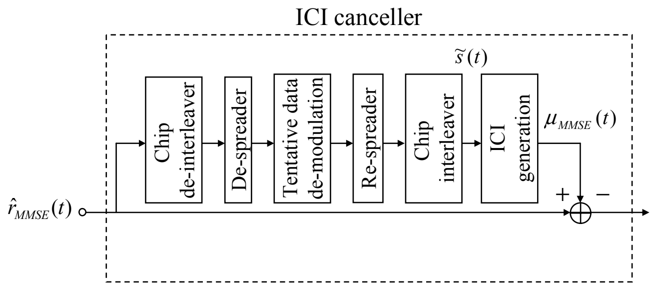
which is the soft decision value for succeeding data demodulation on $d(n)$.

D. ICI cancellation

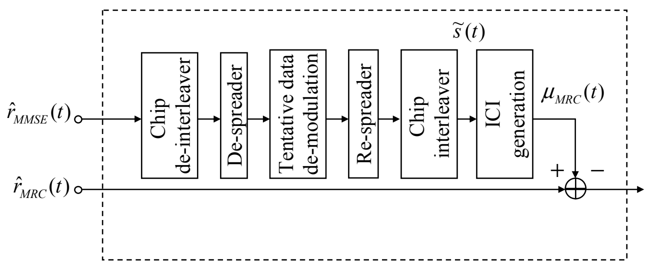
As will be described in Sect. III A, for the case of large *SF*, ICI can be sufficiently suppressed by despreading process. However, for the case of small *SF*, the ICI suppression is not sufficient and the achievable BER performance degrades. In this paper, three types of ICI cancellers are proposed. Fig. 3 shows their structures. The equalized time-domain chip sequence $\hat{r}(t)$ after MMSE-FDE and MRC-FDE is denoted as $\hat{r}_{MMSE}(t)$ and $\hat{r}_{MRC}(t)$, respectively. In type I and type II, after despreading of $\hat{r}_{MMSE}(t)$, tentative data demodulation, re-spreading and chip interleaving is carried out to generate the chip sequence $\tilde{s}(t)$. After chip-interleaving, type I generates the ICI replica $\mu_{MMSE}(t)$ by substituting $\tilde{s}(t)$ into Eq. (11). Then, $\mu_{MMSE}(t)$ is subtracted from $\hat{r}_{MMSE}(t)$ and despreading and data-demodulation is carried out again. In type II, the ICI replica $\mu_{MRC}(t)$ is generated and subtracted from $\hat{r}_{MRC}(t)$. From Eq. (11), $\mu_{MMSE}(t)$ and $\mu_{MRC}(t)$ are obtained using

$$\mu_{MMSE\,(\text{or } MRC)}(t) = \sqrt{\frac{2E_c}{T_c}} \frac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{H}(k) \left[\sum_{\substack{\tau=0 \\ \neq t}}^{N_c-1} \tilde{s}(\tau) \exp\left(j2\pi k \frac{t-\tau}{N_c} \right) \right] ,(13)$$

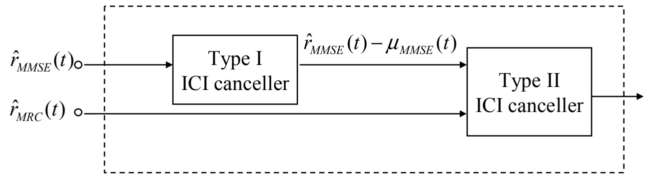
where $\hat{H}(k)$ is given by Eq. (8) for MMSE and MRC-FDE. It can be understood from Eqs. (11) and (13) that ICI cancellation is perfect when tentative data demodulation is correct (i.e., $\tilde{s}(\tau) = s(\tau)$ for all τ). Type II can maximize the SNR after ICI cancellation if tentative data demodulation is correct. Type III is an enhanced version of type II that uses the type I for improving the ICI replica generation.



(a) Type I



(b) Type II



(c) Type III

Figure 3. Proposed ICI canceller.

III. COMPUTER SIMULATION

The simulation parameters are summarized in Table 1. We assume Quaternary phase shift keying (QPSK) data modulation, the FFT window size of N_c=256 chips and the GI of N_g=32 chips. The *SF* x N_c block interleaver is used as chip inverleaver as shown in Fig.4. Fading channel is assumed to be a frequency-selective fading channel having an *L*-path uniform power delay profile. Block fading with $f_D T_c N_c$=0.001, where the path gains stay constant over one data frame, is assumed. Perfect chip timing and ideal channel estimation are assumed.

TABLE I. SIMULATION PARAMETERS

Transmitter	Modulation	QPSK
	Number of FFT points	N_c=256
	GI	N_g=32(chip)
	Spreading sequence	Long PN sequence
	Spreading factor	*SF*=1~64
Channel	Fading	Frequency -selective block Rayleigh fading
	Power delay profile	*L*=16-path uniform power delay profile
Receiver	Number of receive antennas	N_r=1,2
	Frequency-domain equalization	MRC, MMSE
	Channel estimation	Ideal

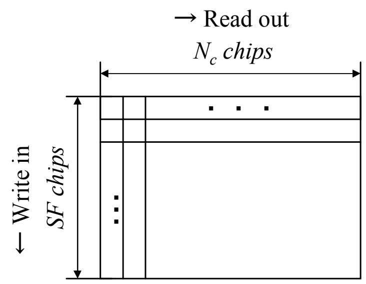


Figure 4. Chip interleaver.

A. BER performance without ICI cancellation

Without ICI canceller, no chip interleaving is necessary. The simulated BER performances with MMSE and MRC equalizations are plotted in Fig. 5 as a function of the average received bit energy-to-AWGN noise power spectrum density ratio E_b/N_0, given by E_b/N_0=*SF*$(1+N_g/N_c)(E_c/N_0)$, for the case of N_r=1 (no antenna diversity), *L*=16, $f_D \to 0$ and α=0 dB. The BER floors are seen with MRC equalization for *SF*=1 and 4, due to the large ICI produced by the enhanced frequency-selectivity. When *SF*=16 and 64, however, the MRC equalization can achieve almost the same BER performance as MMSE equalization since the ICI can be sufficiently suppressed by the despreading process. On the other hand, the MMSE equalization always achieves a better BER performance than MRC. No BER floors are seen for MMSE-FDE and BER performance improves as *SF* increases.

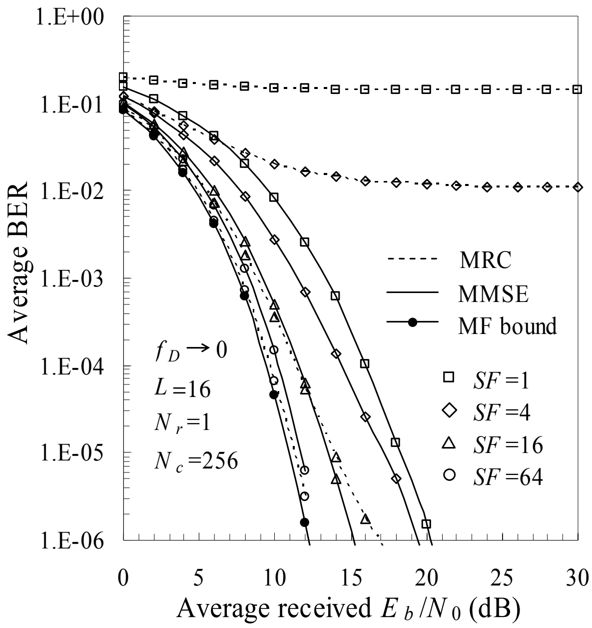


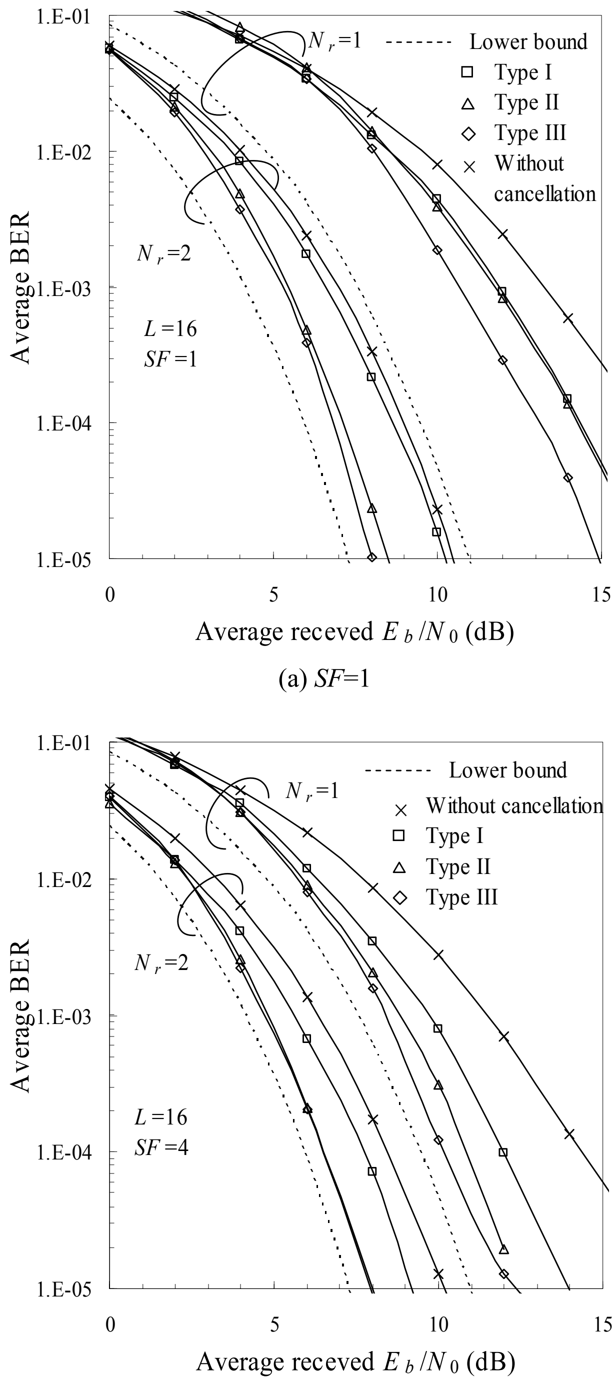
Figure 5. Simulated BER performance without ICI cancellation.

B. BER performance with ICI cancellation

The simulated BER performance with ICI cancellation is plotted in Fig. 6 as a function of the average received E_b/N_0. For comparison, the performance using MMSE-FDE without ICI cancellation and the theoretical lower bound are also plotted. Type II gives better BER performance than type I since type II can maximize the SNR if tentative data demodulation is correct. It can be seen that type III can further improve the BER performance. This is because type III uses the ICI-reduced chip sequence obtained by type I canceller for improved ICI replica generation.

First, we consider the case of *SF*=1 (nonspread SC system) when N_r=1 (no diversity). With type III, an E_b/N_0 reduction of about 3.1 dB is achieved for BER=10^{-4} from the case without cancellation. The E_b/N_0 degradation from the lower bound is 3.7 dB (about 0.5 dB out of which is due to the GI insertion). The use of antenna diversity combining is effective to further improve the BER performance. Type III with antenna diversity provides the BER performance close to the lower bound by about 0.9 dB.

When SF=4, the performance is better than the case of SF=1. This is because ICI can be suppressed by despreading process when SF=4. Similar to the case of SF=1, Type III provides better BER performance than Type I and Type II. With type III, the E_b/N_0 reduction for BER=10^{-4} from the case without cancellation is as much as about 4.2 dB. The E_b/N_0 degradation from the lower bound is only 0.7 dB (it is 3.7 dB when SF=1). When N_r=2, the BER performance with Type III approaches the lower bound by about 0.6 dB.



(a) SF=1

(b) SF=4

Figure 6. Simulated average BER performance with ICI cancellation.

IV. CONCLUSION

In this paper, ICI cancellation for DS-CDMA with FDE was proposed and the BER performance was evaluated by computer simulation to show that significant performance improvement can be achieved for the case of small spreading factor. Three types of ICI canceller were presented. Type III uses the ICI-reduced chip sequence obtained by type I canceller for improved ICI replica generation, thereby, achieving the best BER performance. When SF=1(4), the E_b/N_0 reduction for BER=10^{-4} from the case without cancellation was found to be about 3.1(4.2) dB. The use of two-branch antenna diversity is beneficial and the performance close to the lower bound by about 0.6 dB is obtained when SF=4.

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