Iterative Frequency-domain Inter-chip Interference Cancellation for DS-CDMA

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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 an iterative frequency-domain ICI cancellation (FD-ICIC) scheme for DS-CDMA. In the proposed scheme, the equalization weight is updated for each iteration taking into account the residual ICI with FDE. It is found by computer simulation that the proposed iterative FD-ICIC can significantly improve the BER performance and the E_b/N_0 reduction for BER=10^{-4} from no ICI cancellation case is as much as 4.2 dB when *SF*=4. The BER performance at the 2nd iteration approaches the theoretical lower bound by about 0.7 dB (including a 0.5 dB loss due to the GI insertion).**

Key words: DS-CDMA, FDE, Inter-chip interference cancellation

1. INTRODUCTION

Wireless channel is composed of many propagation paths with different time delays, producing frequency-selective fading [1]. Direct-sequence code division multiple access (DS-CDMA) can exploit the channel frequency-selectivity by the use of coherent rake combining that resolves the propagation paths having different time delays and coherently combines them to achieve the path diversity effect [2]. In the 3rd generation (3G) mobile communication systems, wideband DS-CDMA with rake combining [3] has been adopted as a wireless access technique for data transmissions of up to a few Mbps. Recently, demands for broadband services are increasing in mobile communication systems and a lot of research attention is paid to the next generation mobile communication systems that support transmission data rates higher than few tens of Mbps [4]. However, the channel for such high speed data transmission becomes severely frequency-selective and the bit error rate (BER) performance with rake combining degrades due to strong inter-path interference. Hence, the use of some channel equalization techniques is indispensable.

Multi-carrier code division multiple access (MC-CDMA) can exploit the channel frequency-selectivity by using simple one-tap frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion and therefore, has been attracting much attention for the downlink transmission [5~7]. Recently, it was shown [8,9] that, in DS-CDMA, MMSE-FDE can replace the rake combining and give almost the same downlink performance as in MC-CDMA.

DS-CDMA has the flexibility to provide multi-rate transmissions for the given chip rate (or for the given spreading bandwidth) simply by changing the spreading factor *SF*. However, for a small *SF*, residual inter-chip-inference (ICI) is present after MMSE-FDE and it degrades the BER performance [9]. In this paper, we propose an iterative frequency-domain ICI cancellation (FD-ICIC) scheme for DS-CDMA with MMSE-FDE. In the proposed scheme, the equalization weight is updated for each iteration taking into account the residual ICI. The BER performance with FD-ICIC is evaluated by computer simulation.

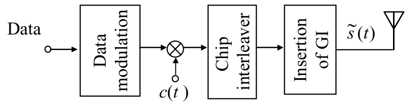
Remainder of this paper is organized as follows. Section 2 presents the transmission system model for DS-CDMA with FDE to show the presence of residual ICI. In Section 3, the proposed frequency-domain ICI cancellation is presented. In Section 4, the achievable BER performance in a frequency-selective Rayleigh fading channel is evaluated by computer simulation and the improvement of the proposed ICI cancellation is shown. Section 5 provides some conclusions.

2. Frequency-interleaved CDMA with MMSE-FDE

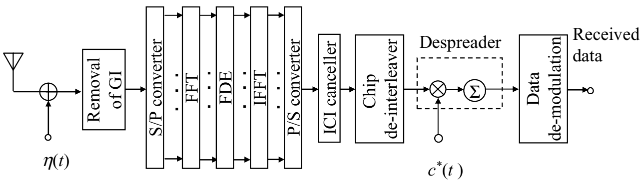
2.1. Overall transmission system

Transmitter/receiver structure of DS-CDMA with FDE 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 the spreading sequence $c(t)$. The resultant 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 blocks of N_c+N_g chips each, as illustrated in Fig. 2.

The GI-inserted block is transmitted over a frequency-selective fading channel and is received at the receiver. After the removal of GI, the received block is decomposed by N_c-point fast Fourier transform (FFT) into N_c subcarrier components (the terminology "subcarrier" is used for explanation purpose only although subcarrier modulation is not used). Then, FDE is carried out in the frequency-domain [8,9]. Finally, inverse FFT (IFFT) is applied to obtain the time-domain equalized chip sequence for despreading and data demodulation.



(a) Transmitter



(b) Receiver

Figure 1 Transmitter/receiver structure.

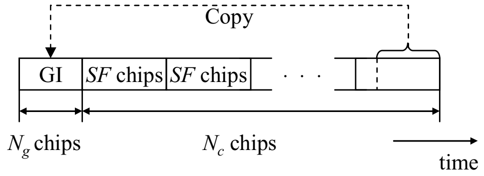


Figure 2 Block structure.

2.2. Transmit and Received signals

Throughout this paper, chip-spaced time representation of transmitted signals is used. Without loss of generality, a transmission of the data symbol sequence $\{d(n);\ n=0\sim N_c/SF-1\}$ is considered, where N_c and SF are chosen so that the value of N_c/SF becomes an integer. The GI-inserted chip sequence $\{\hat{s}(t);\ t=-N_g\sim N_c-1\}$ for one block of N_c+N_g chips can be expressed, using the equivalent lowpass representation, as

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

where E_c and T_c denote the chip energy and the chip duration, respectively, and $s(t)$ is given by

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

for $t=0\sim N_c-1$, where $\lfloor x\rfloor$ represents the largest integer smaller than or equal to x.

The propagation channel is assumed to be a frequency-selective block fading channel having chip-spaced L discrete paths, each subjected to independent fading. The assumption of block fading means that the path gains remain constant over at least one block duration. The impulse response $h(t)$ of multipath channel can be expressed as

$$h(t)=\sum_{l=0}^{L-1}h_l\delta(t-\tau_l)\qquad ,(3)$$

where h_l and τ_l are the complex-valued path gain and time delay of the lth path ($l=0\sim L-1$), respectively, with $\sum_{l=0}^{L-1}\mathrm{E}[|h_l|^2]=1$ (E[.] denotes the ensemble average operation). The chip sequence $\{r(t);\ t=-N_g\sim N_c-1\}$ in a block can be expressed as

$$r(t)=\sum_{l=0}^{L-1}h_l\hat{s}(t-\tau_l)+\eta(t)\quad ,(4)$$

where $\eta(t)$ is a zero-mean complex Gaussian process with 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.

2.3. FDE and Despreading

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

$$\begin{aligned}R(k)&=\sum_{t=0}^{N_c-1}r(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\&=\sqrt{2E_c/T_c}H(k)S(k)+\Pi(k)\end{aligned}\quad ,(5)$$

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

$$\begin{cases}S(k)=\sum_{t=0}^{N_c-1}s(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\H(k)=\sum_{l=0}^{L-1}h_l\exp\left(-j2\pi k\frac{\tau_l}{N_c}\right)\\\Pi(k)=\sum_{t=0}^{N_c-1}\eta(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\end{cases}\quad .(6)$$

Then, FDE is carried out as follows:

$$\begin{aligned}\hat{R}(k) &= R(k)w(k)\\ &= \sqrt{2E_c/T_c}\,S(k)\hat{H}(k)+\hat{\Pi}(k)\end{aligned} \quad (7)$$

with

$$\begin{cases}\hat{H}(k)=w(k)H(k)\\ \hat{\Pi}(k)=w(k)\Pi(k)\end{cases}, \quad (8)$$

where $w(k)$ is the equalization weight and $\hat{H}(k)$ and $\hat{\Pi}(k)$ are the equivalent channel gain and the noise component after FDE, respectively.

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

$$\begin{aligned}\hat{r}(t) &= \frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{R}(k)\exp\left(j2\pi t\frac{k}{N_c}\right)\\ &= \sqrt{\frac{2E_c}{T_c}}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{H}(k)\right)s(t)+\mu(t)+\hat{\eta}(t)\end{aligned}, \quad (9)$$

where $s(t)$ in the first term represents the transmitted signal component, the second term $\mu(t)$ is the residual ICI component and the third term $\hat{\eta}(t)$ is the noise component. $\mu(t)$ and $\hat{\eta}(t)$ can be expressed as

$$\begin{cases}\mu(t)=\sqrt{\frac{2E_c}{T_c}}\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{H}(k)\left[\sum_{\substack{\tau=0\\ \neq t}}^{N_c-1}s(\tau)\exp\left(j2\pi k\frac{t-\tau}{N_c}\right)\right]\\ \hat{\eta}(t)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{\Pi}(k)\exp\left(j2\pi k\frac{t}{N_c}\right)\end{cases}. \quad (10)$$

If $\hat{H}(k)\neq$ constant (i.e., frequency-selective channel), $\mu(t)\neq 0$, and hence the ICI is produced. Despreading is carried out on $\hat{r}(t)$, giving

$$\hat{d}(n)=\frac{1}{SF}\sum_{t=nSF}^{(n+1)SF-1}\hat{r}(t)c^{*}(t), \quad (11)$$

which is the decision variable for data demodulation on $d(n)$.

3. Iterative frequency-domain ICI cancellation

As understood from Eq. (9), the residual ICI $\mu(t)$ may degrade the BER performance in a frequency-selective fading channel. In this paper, ICI cancellation is incorporated into MMSE-FDE to improve the BER performance. For the proposed iterative FD-ICIC, we use the following frequency-domain representation for residual ICI component $\mu(t)$:

$$M(k)=\sqrt{\frac{2E_c}{T_c}}\left\{\hat{H}(k)-\frac{1}{N_c}\sum_{k'=0}^{N_c-1}\hat{H}(k')\right\}S(k) \quad .(12)$$

DS-CDMA receiver structure using the proposed iterative FD-ICIC is illustrated in Fig. 3. Below, we consider the ith iteration.

After despreading is carried out on ICI-reduced chip sequence $\tilde{r}^{(i-1)}(t)$ in the (i–1)th iteration, tentative data decision is performed. Then, data modulation and spreading are carried out to generate the replica $\tilde{s}^{(i)}(t)$ of the transmitted chip sequence $s(t)$. N_c-point FFT is applied to decompose the replica $\tilde{s}^{(i)}(t)$ into N_c subcarrier components $\{\tilde{S}^{(i)}(k); k=0\sim(N_c-1)\}$. The ICI replica $\tilde{M}^{(i)}(k)$ for the ith iteration is generated by replacing $S(k)$ by $\tilde{S}^{(i)}(k)$ in Eq. (12).

In the ith iteration, FDE is carried out, using the equalization weight $w^{(i)}(k)$, as

$$\hat{R}^{(i)}(k)=R(k)w^{(i)}(k)=\sqrt{\frac{2E_c}{T_c}}S(k)\hat{H}^{(i)}(k)+\hat{\Pi}^{(i)}(k) \quad ,(13)$$

where $\hat{H}^{(i)}(k)$ and $\hat{\Pi}^{(i)}(k)$ are the equivalent channel gain and the noise component after FDE, respectively. $w_m^{(i)}(k)$ is given by

$$w^{(i)}(k)=\frac{H^{*}(k)}{\beta^{(i)}|H(k)|^2+(E_c/N_0)^{-1}} \quad ,(14)$$

where $0\leq\beta^{(i)}\leq 1$. $\beta^{(i)}=0$ gives the MRC weight that maximizes the signal-to-noise ratio (SNR) at each subcarrier, while $\beta^{(i)}=1$ gives the MMSE weight.

After carrying out FDE, frequency-domain ICI cancellation is performed as

$$\tilde{R}^{(i)}(k)=\hat{R}^{(i)}(k)-\tilde{M}^{(i)}(k) \quad .(15)$$

Finally, a series of IFFT, despreading and data-demodulation is carried out again to recover the transmitted data.

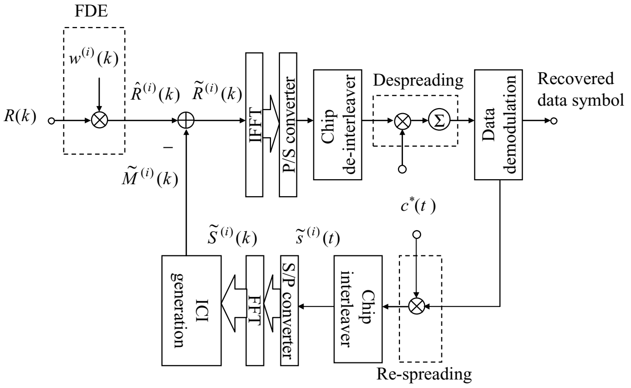


Figure 3 Iterative FD-ICIC structure.

4. Computer simulation

The simulation parameters are summarized in Table 1. We assume quaternary phase shift keying (QPSK) data modulation and 16-quadrature amplitude modulation (16QAM), FFT block size of N_c=256 chips and GI of N_g=32 chips. Fading channel is assumed to be a frequency-selective block Rayleigh fading channel having a chip-spaced L-path uniform power delay profile (i.e., $E[|h_{m,l}|^2]=1/L$ for all m and l) and the normalized maximum Doppler frequency $f_DT_cN_c$=0.001 (this corresponds to a mobile terminal traveling speed of 75km/h for a chip rate of 100Mcps and 5GHz carrier frequency). Perfect chip timing and ideal channel estimation are assumed.

Table 1: Simulation parameters

Transmitter	Modulation	QPSK, 16QAM
	Number of FFT points	N_c=256
	GI	N_g=32(chip)
	Spreading sequence	Long PN sequence
	Spreading factor	SF=1,4
Channel	Fading	Frequency -selective block Rayleigh fading
	Power delay profile	L=16-path uniform power delay profile
Receiver	Channel estimation	Ideal

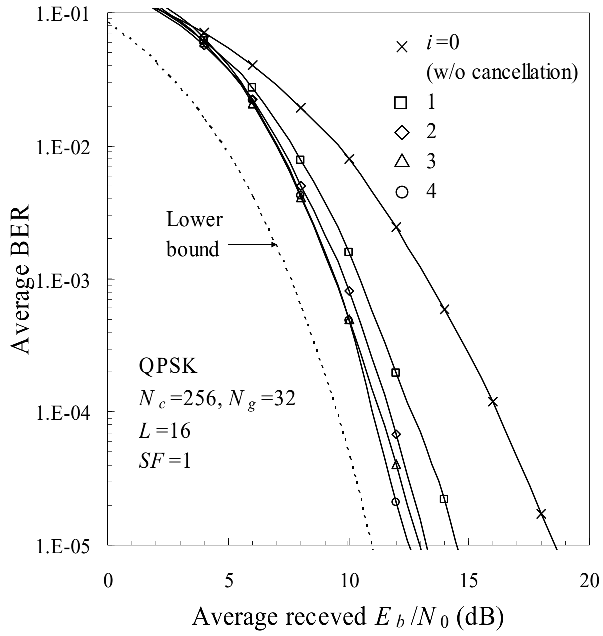
The simulated BER performance of DS-CDMA with iterative FD-ICIC is plotted in Fig. 4 for QPSK as a function of the average received bit energy-to-AWGN noise power spectrum density ratio E_b/N_0, defined as $E_b/N_0=(1/M)SF(E_c/N_0)(1+N_g/N_c)$, when SF=1 and 4. Here, M is the modulation level. For comparison, the theoretical lower bound [8] is also plotted. For the case of SF=1 (see Fig. 4 (a)), the optimum $\beta^{(i)}$ in the equalization weight was found by computer simulation as $\beta^{(0)}$=1, $\beta^{(1)}$=0.2, $\beta^{(2)}$=0.1, $\beta^{(3)}$=0.05 and $\beta^{(4)}$=0. The BER performance with i=0 corresponds to the case of MMSE-FDE without ICI cancellation. It can be seen from Fig. 4 (a) that FD-ICIC can significantly improve the BER performance. When i=4, the E_b/N_0 reduction for BER=10^{-4} from the case without ICI cancellation is as much as 5.2 dB and the BER performance gets close to the theoretical lower bound by about 1.6 dB (including a 0.5 dB loss due to the GI insertion).

For the case of SF=4 (see Fig. 4 (b)), the optimum $\beta^{(i)}$ was set as $\beta^{(0)}$=1, $\beta^{(1)}$=0.1 and $\beta^{(2)}$=0. The BER performance with SF=4 is better than that with SF=1 since the residual ICI can be sufficiently suppressed by the despreading process. The E_b/N_0 reduction of 4.2 dB from the case without ICI cancellation is obtained and the BER performance at the 2nd iteration approaches the theoretical lower bound by about 0.7 dB.

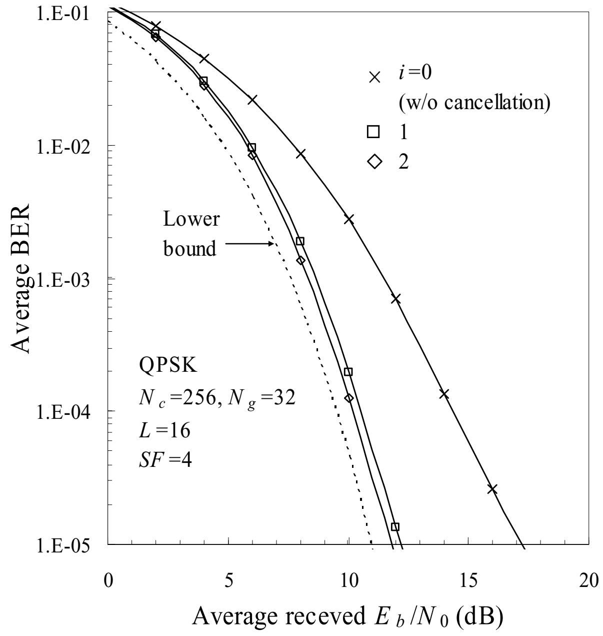
The simulated BER performance with 16QAM is plotted in Fig. 5 when SF=1. $\beta^{(i)}$ was taken to be $\beta^{(0)}$=1, $\beta^{(1)}$=0.15, $\beta^{(2)}$=0.1, $\beta^{(3)}$=0.05 and $\beta^{(4)}$=0.05. For 16QAM, the Euclidean distance between different symbols is shorter and hence, decision errors due to the residual ICI are more likely than for QPSK. FD-ICIC is very effective to improve the BER performance even for 16QAM. The E_b/N_0 reduction of as much as 5.6 dB can be achieved for BER=10^{-4}.

5. Conclusion

In this paper, an iterative frequency-domain ICI cancellation (FD-ICIC) for DS-CDMA with MMSE-FDE was proposed. The equalization weight is updated for each iteration taking into account the residual ICI. The BER performance with the proposed FD-ICIC was evaluated by computer simulation. It was found that, when SF=4, the E_b/N_0 reduction for achieving BER=10^{-4} from no cancellation case is as much as about 4.2 dB and the performance approaches the theoretical lower bound by about 0.7 dB.



(a) SF=1.



(b) SF=4.

Figure 4 Simulated BER performance with FD-ICIC for QPSK.

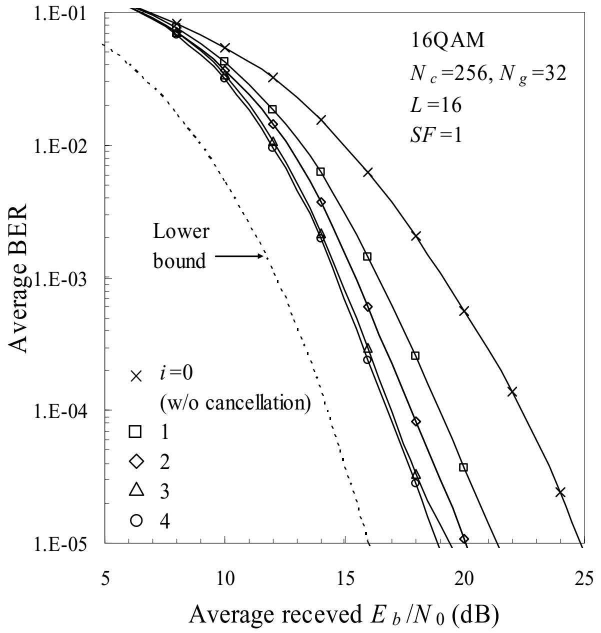


Figure 5 Simulated BER performance with FD-ICIC for 16QAM.

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