FREQUENCY-DOMAIN EQUALIZATION FOR ANTENNA DIVERSITY RECEPTION OF DS-CDMA SIGNALS

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ABSTRACT

A coherent rake combiner is employed as the channel matched filter in a DS-CDMA mobile radio. However, as the number of propagation paths increases, the coherent rake receiver incurs a serious degradation in the bit error rate (BER) performance due to severe inter-path interference (IPI). In this paper, frequency-domain equalization employed in multi-carrier code division multiple access (MC-CDMA) is applied to achieve the frequency diversity effect while suppressing IPI for the antenna diversity reception of DS-CDMA signals. The BER performance improvement in a frequency-selective Rayleigh fading channel is evaluated by computer simulation.

KEYWORD DS-CDMA, frequency-domain equalization, MMSE, frequency-selective fading

1. INTRODUCTION

In the frequency-selective fading channel, if an advanced equalization technique is not applied, the bit error rate (BER) performance of single carrier (SC) transmission is significantly degraded due to severe inter-symbol interference (ISI) [1]. Recently, direct sequence code division multiple access (DS-CDMA) has been used for improving the BER performance of around a few Mbps transmissions by employing rake combining [2] to exploit the frequency-selectivity of the fading channel [3]. However, the rake combiner requires as many fingers (correlators) as the number of propagation paths to collect most of the transmitted power, otherwise a significant performance degradation occurs [4] and hence, the complexity of rake combiner increases. Furthermore, the large inter-path interference (IPI) degrades the BER performance even with ideal rake combining. These pose the limitation to the application of DS-CDMA technique to high speed data transmissions in a severe frequency-selective fading channel.

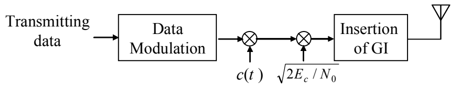
Recent studies have been shifted from DS-CDMA to multicarrier (MC) transmission techniques to overcome the frequency-selectivity of the fading channel by applying parallel transmission using many orthogonal subcarriers [5-8]. Much attention has been paid to orthogonal frequency division multiplexing (OFDM) and MC-CDMA. MC-CDMA has been considered a promising candidate for broadband wireless multi-access [9]. Using one-tap frequency-domain equalization (FDE), much better BER performance can be attained with MC-CDMA than with DS-CDMA [10]. However, there is a drawback in MC transmission, i.e., linear transmit power amplifiers with large peak-to-average power ratio (PAPR) are necessary. More recently, application of FDE to orthogonal multicode DS-CDMA transmission (used in the forward link of cellular DS-CDMA communications systems) has been proposed [11] in order to reduce the multi-access interference (MAI) resulting from IPI and accordingly, improves its BER performance in a frequency-selective fading channel.

In this paper, we apply FDE to the antenna diversity reception of DS-CDMA signals to achieve the frequency diversity effect while reducing the adverse effect of IPI. Remainder of this paper is organized as follows. Section 2 presents the transmission system model for a single-code DS-CDMA using FDE and antenna diversity reception. Three types of FDE are considered: minimum mean square error (MMSE) equalization, maximal-ratio combining (MRC) equalization and zero-forcing (ZF) equalization. The achievable BER performance in a frequency-selective Rayleigh fading is evaluated by computer simulation. Performance comparison of FDE and rake combining is presented. Section 4 offers some conclusions.

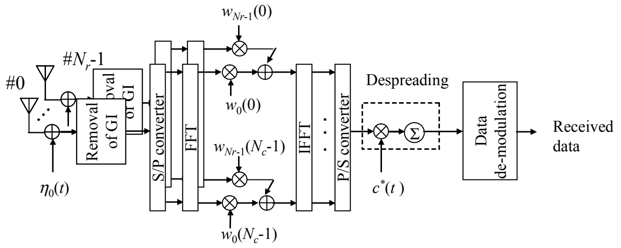
2. DS-CDMA WITH FDE AND ANTENNA DIVERSITY RECEPTION

2.1 Transmission system model

Transmission system model for DS-CDMA using FDE and antenna diversity reception is illustrated in Fig.1. At the transmitter, the binary data sequence is transformed into data-modulated symbol sequence $\{d(n)\}$ and then spread by multiplying the spreading sequence $\{c(t)\}$ with a spreading factor of SF. The resulting 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 frame of N_c+N_g chips. Figure 2 illustrates the frame structure. Transmitted chip sequence over a frequency-selective fading channel is received by each of the N_r diversity antennas at the receiver. The received chip sequence on each antenna is decomposed by N_c-point fast Fourier transform (FFT) into N_c subcarrier components (although DS-CDMA does not apply subcarrier modulation unlike MC-CDMA and OFDM, we use the terminology "subcarrier"). Then, joint FDE and antenna diversity reception is carried out and inverse FFT (IFFT) is applied to obtain the equalized and diversity combined time-domain chip sequence for despreading and data demodulation.



(a) Transmitter



(b) Receiver

Fig.1 Transmission system model for DS-CDMA with FDE and antenna diversity reception.

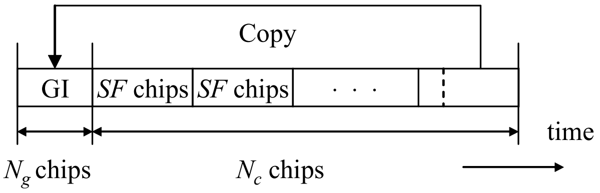


Fig.2 Frame structure.

2.2 Received signal

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

$$s(t)=\sqrt{2E_c/T_c}\,d(\lfloor t/SF\rfloor)c(t),\ t=-N_g\sim N_c\text{-}1,\ (1)$$

where E_c and T_c denote the chip energy and the chip duration, respectively, and $\lfloor x\rfloor$ 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 τ_l of the lth path (l=0~L-1) is assumed to be $\tau_l=l$ chips. The chip sequence $\{r_m(t);\ m=0\sim N_r\text{-}1,\ t=-N_g\sim N_c\text{-}1\}$ received on the mth antenna can be represented as

$$r_m(t)=\sum_{l=0}^{L-1}\xi_{l,m}s(t-l)+\eta_m(t),\quad (2)$$

where $\xi_{l,m}$ is the complex path gain experienced at the m antenna with $\sum_{l=0}^{L-1}E[|\xi_{l,m}|^2]=1$ (E[.] denotes the ensemble average operation) and $\eta_m(t)$ is the noise process with zero-mean and variance of $2N_0/T_c$ with N_0 being the single-sided power spectrum density of the additive white Gaussian noise (AWGN) process. In this paper, we assume a block fading, where the path gains stay constant over one frame duration.

2.3 Joint FDE and antenna diversity reception

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

$$R_m(k)=H_m(k)S(k)+N_m(k)\ ,\ (3)$$

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

$$\begin{cases}S(k)=\sum_{t=0}^{N_c-1}s(t)\exp\left(-j2\pi k\dfrac{t}{N_c}\right)\\ H_m(k)=\sum_{l=0}^{L-1}\xi_{l,m}\exp\left(-j2\pi k\dfrac{l}{N_c}\right)\\ N_m(k)=\sum_{t=0}^{N_c-1}\eta_m(t)\exp\left(-2\pi k\dfrac{t}{N_c}\right)\end{cases}.\ (4)$$

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

$$\tilde{R}(k)=\sum_{m=0}^{N_r-1}R_m(k)w_m(k),\ (5)$$

where $w_m(k)$ is the equalization weight. We consider MMSE equalization, MRC equalization and ZF equalization. The MRC weight maximizes the signal-to-noise ratio (SNR) at each subcarrier. The MMSEC weight is chosen so that the mean square error (MSE) between $S(k)$ and $\tilde{R}(k)$ is minimized, while the ZF weight is chosen to get $E[\tilde{R}(k)]=S(k)$. They are given by

$$w_m(k)=\begin{cases}\dfrac{H_m^*(k)}{\sum_{m=0}^{N_r-1}|H_m(k)|^2+(E_c/N_0)^{-1}}, & \text{MMSE}\\ H_m^*(k), & \text{MRC}\\ \dfrac{H_m^*(k)}{\sum_{m=0}^{N_r-1}|H_m(k)|^2}, & \text{ZF}\end{cases},\ (6)$$

where E_c/N_0 is the average chip energy-to-AWGN power spectrum density ratio and * denotes complex conjugation. N_c-point IFFT is applied to $\{\tilde{R}(k);k=0\sim N_c-1\}$ to obtain the time-domain chip sequence. Finally, despreading is carried out for succeeding data demodulation.

3. COMPUTER SIMULATION

3.1 Simulation condition

The simulation parameters are summarized in Table 1. We assume binary phase shift keying (BPSK) data and spreading modulation, an FFT window size of N_c=256 chips and a GI of N_g=32 chips. The fading channel is assumed to be a frequency-selective block fading channel having an L-path exponential power delay profile with a decay factor of α. Perfect chip timing and ideal channel estimation are assumed

Table 1 Simulation parameters

Transmitter	Modulation	BPSK
	Number of FFT points	N_c=256
	GI	N_g=32(chip)
	Spreading sequence	Long PN sequence
	Spreading factor	SF=1~256
Channel	Fading	Frequency -selective block Rayleigh fading
	Power delay profile	L=16-path exponential power delay profile
		Decay factor α=0,8(dB)
Receiver	Number of receive antennas	N_r=1,2,4
	Frequency-domain equalization	MRC,ZF,MMSE
	Channel estimation	Ideal

3.2 Comparison of MMSE, MRC and ZF equalizations

The simulated BER performances of DS-CDMA using MMSE, MRC and ZF equalizations are compared in Fig. 3 as a function of the average 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 no antenna diversity (N_r=1) and decay factor α=0 dB. It can be seen from the figure that the ZF equalization gives the same BER performance for all SF values since the perfect frequency-nonselective channel is restored. The BER floors are seen with MRC equalization for SF=1 and 4, due to the larger ISI 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 ISI can be sufficiently suppressed during the despreading process. On the other hand, the MMSE equalization always achieves the best BER performance. Hence, in the following, we use the MMSE equalization only.

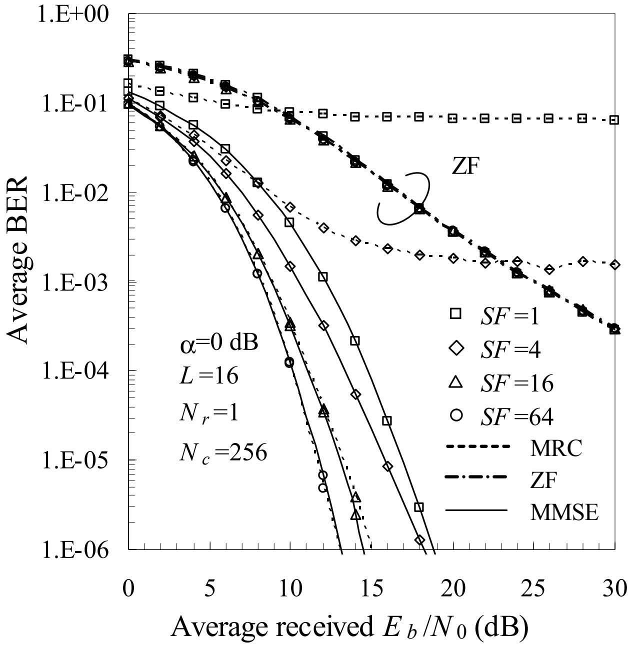
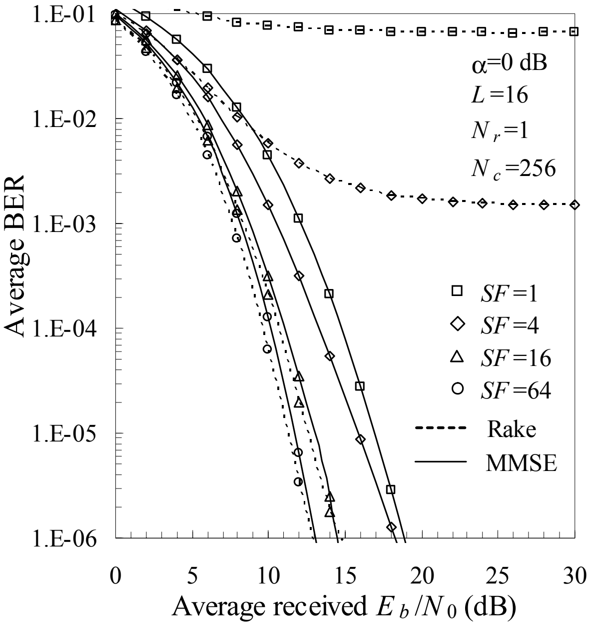


Fig. 3 Simulated BER performances of DS-CDMA using MMSE, MRC and ZF equalizations. No antenna diversity (N_r=1), L=16 and α=0 dB.

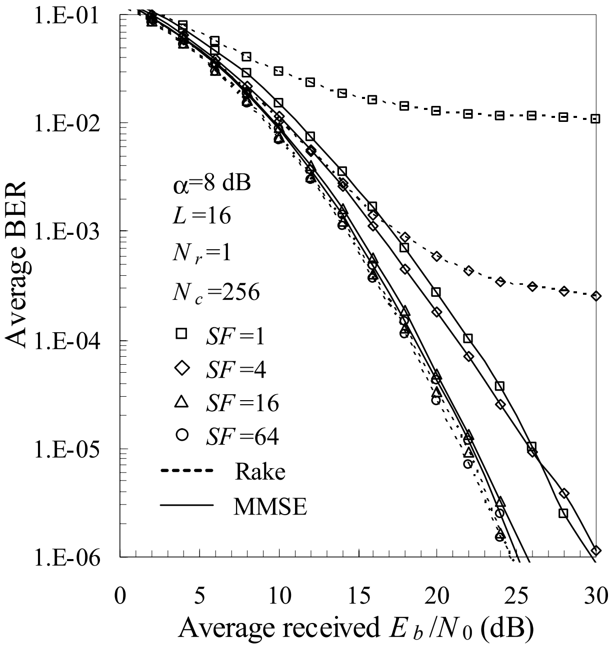
3.3 Comparison of MMSE equalization and rake combining

Figure 4 illustrates the average BER performances of DS-CDMA using MMSE equalization and using rake combining with SF as a parameter for α=0 dB (strong frequency-selectivity) and 8dB (weak frequency-selectivity). It is seen from the figure that, for small SF values (i.e., SF=1 and 4), MMSE equalization provides better BER performance than rake combing; BER floors are seen with rake combining due to strong IPI, but no BER floors are seen with MMSE equalization. Note that BER floors when α=8 dB are smaller than when α=0dB due to less IPI. However, it should be noted that using large SF (i.e., SF=64), rake combining can effectively suppress the IPI and thus, can achieve slightly better BER performance than MMSE equalization. This slight performance inferiority of about 0.5dB in the required E_b/N_0 observed in the MMSE equalization is due to the power loss resulting from the GI insertion.

An improved BER performance achieved when α=0 dB compared to the case when α=8 dB is due to the effect of frequency diversity for MMSE equalization (the effect of path diversity for rake combining); the reduction in the required E_b/N_0 for achieving BER=10^{-4} when α=0 dB from the case when α=8 dB is as much as about 8.5 dB.



(a) α=0 dB

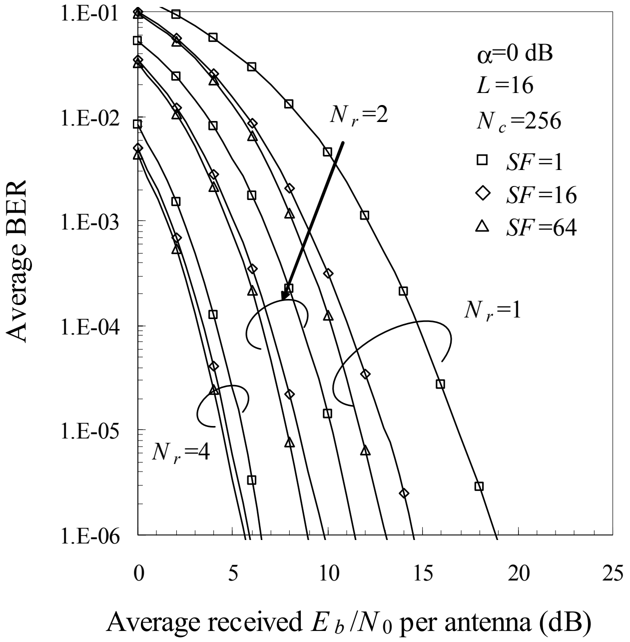


(b) α=8 dB

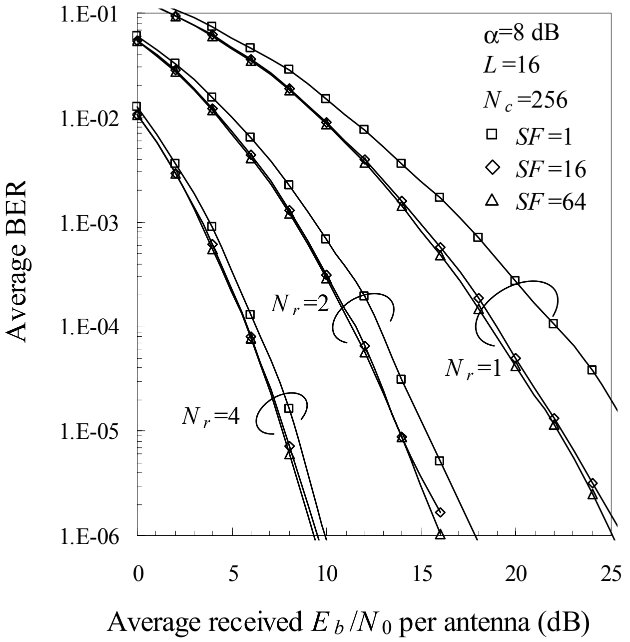
Fig. 4 Simulated average BER performances of DS-CDMA with MMSE equalization and with rake combining with SF as a parameter for α=0 and 8 dB. No antenna diversity (N_r=1).

3.4 Joint MMSE equalization and antenna diversity combining

The simulated BER performance with joint MMSE equalization and antenna diversity combining is plotted in Fig. 5 with the number N_r of diversity antennas and the spreading factor SF as parameters when α=0 and 8 dB. It can be clearly seen that the use of antenna diversity combining is always beneficial irrespective of SF. Since larger frequency diversity effect is obtained when α=0 dB, the additional performance improvement due to antenna diversity combining is smaller than when α=8 dB. However, when SF=64, an antenna diversity gain of as much as about 7dB can still be achieved for BER=10^{-4} by the use of N_r=4-branch antenna diversity combining.



(a) α=0 dB



(b) α=8 dB

Fig. 5 Simulated BER performance with joint MMSE equalization and antenna diversity reception with the number N_r of diversity antennas and SF as parameters when α=0 and 8 dB.

3.5 Performance comparison with nonspread SC transmission

It is seen in Fig. 3 that the BER performance improves as *SF* increases and the required E_b/N_0 value for achieving BER=10^{-4} can be reduced by about 5 dB when *SF*=256 compared to the case of *SF*=1. Using *SF*=1 is equivalent to the nonspread SC transmission. Hence, the DS-CDMA using FDE can achieve better BER performance at the cost of reducing the data rate or increasing the bandwidth for the same data rate. It is interesting to compare the BER performances of DS-CDMA and nonspread SC for the same data rate while keeping the bandwidth same. Figure 6 plots the BER performance of orthogonal multicode DS-CDMA using MMSE equalization [11], in which *SF*-code multiplexing is used to achieve the same data rate as the nonspread SC transmission. It can be seen that the achievable BER performance of orthogonal multicode DS-CDMA is almost insensitive to the value of *SF* while achieving the same data rate as SC transmission.

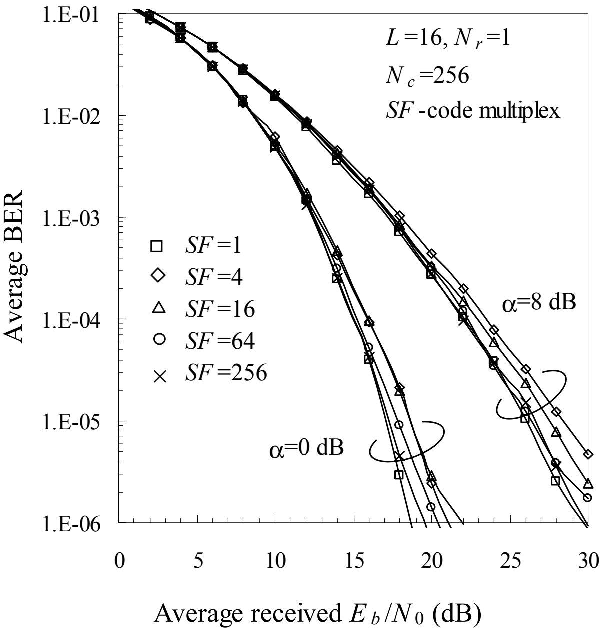


Fig. 6 BER performance of orthogonal multicode DS-CDMA having the same data rate as nonspread SC transmission. Using *SF*=1 is equivalent to the nonspread SC transmission. No antenna diversity (N_r=1) and decay factor α=0 dB.

4. CONCLUSION

In this paper, frequency-domain equalization was presented for the antenna diversity reception of DS-CDMA signals and the achievable BER performance in a frequency-selective Rayleigh fading channel was evaluated by computer simulation. The BER performances using MMSE, MRC and ZF equalizations were compared to find that the MMSE equalization gives the best BER performance. Also found was that as the spreading factor increases, the MMSE equalization improves the BER performance since the ISI produced by the frequency-selectivity can be effectively suppressed. When small spreading factor is used (i.e., *SF*=1 and 4), the BER floors appear when rake combining is used; however, there is no BER floor produced when MMSE equalization is used. It was found that the use of antenna diversity combining is always beneficial irrespective of the degree of frequency-selectivity. When *SF* is large enough (e.g., *SF*=64), almost the same BER performance can be achieved for rake combining and MMSE equalization. However, the use of MMSE equalization is still promising, since as many fingers as the number of resolvable paths are required for rake combining and accurate channel estimation may be difficult on weak paths.

5. REFERENCES

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