Joint Frequency-domain Equalization and Antenna Diversity Combining for Orthogonal Multicode DS-CDMA Signal Transmissions in A Frequency-selective Fading Channel

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Abstract

Orthogonal multicode direct sequence code division multiple access (DS-CDMA) has a flexibility in offering various data rate services. However, in a frequency-selective fading channel, the bit error rate (BER) performance is severely degraded since othogonality among spreading codes is partially lost. In this paper, we apply frequency-domain equalization and antenna diversity combining, used in multi-carrier CDMA (MC-CDMA), to DS-CDMA in order to restore the code othogonality while achieving frequency and antenna diversity effect. It is found by computer simulations that the joint use of frequency-domain equalization and antenna diversity combining can significantly improve the BER performance of orthogonal multicode DS-CDMA in a frequency-selective fading channel.

Keywords

Frequency-domain equalization, antenna diversity, multicode DS-CDMA, frequency-selective fading

1. Introduction

Orthogonal multicode DS-CDMA is flexible in offering various data rate services by changing the number of parallel orthogonal spreading codes [1]. In a DS-CDMA mobile communications system, orthogonal multicode DS-CDMA is used for the downlink; each spreading code is assigned to a different user. In DS-CDMA, the multipath fading channel [2] is resolved by a bank of correlators (known as the rake fingers) into many distinct paths for coherent rake combining. Coherent rake combining can exploit the channel frequency-selectivity to improve the BER performance through path diversity effect (similar effect to antenna diversity) [3]. However, as the number of resolvable paths increases, the receiver complexity increases due to increasing number of rake fingers. Furthermore, increased inter-path interference (IPI) resulting from time asynchronism of different paths offsets the performance improvement by rake combining.

Recently, multi-carrier CDMA (MC-CDMA) has been attracting much attention for broadband wireless multiple access [4]. In MC-CDMA, many orthogonal subcarriers are used and the data symbol to be transmitted is spread over several subcarriers using frequency-domain orthogonal spreading code. At an MC-CDMA receiver, the frequency-domain equalization is applied to the received signal for restoring the code orthogonality. Through frequency-domain equalization and despreading, frequency diversity effect is attained, resulting in significantly improved BER performance of MC-CDMA compared to that of DS-CDMA with coherent rake combining [5].

Quite recentry, application of frequency-domain equalization to single-carrier (SC) transmission has been attracting attention [6]. It is pointed out in [7] that the frequency-domain equalization can be applied to orthogonal multicode DS-CDMA for improving its BER performance in a severe frequency-selective channel. In this paper, joint frequency-domain equalization and antenna diversity combining is considered for the reception of the orthogonal multicode DS-CDMA signals in a severe frequency-selective channel. Section 2 presents weights for joint frequency-domain equalization and antenna diversity combining. Various frequency-domain equalization schemes using maximal ratio combining (MRC), equal gain combining (EGC), orthogonal restoration combining (ORC) and minimum mean square error combining (MMSEC) [8] are considered. In Sect. 3, the achievable BER performances are evaluated by computer simulation. Some conclusions and future work are offered in Sect. 4.

2. Joint Frequency-domain Equalization and Antenna Diversity Reception

Transmission system model of orthogonal multicode DS-CDMA using frequency-domain equalization and antenna diversity combining is illustrated in Fig. 1.

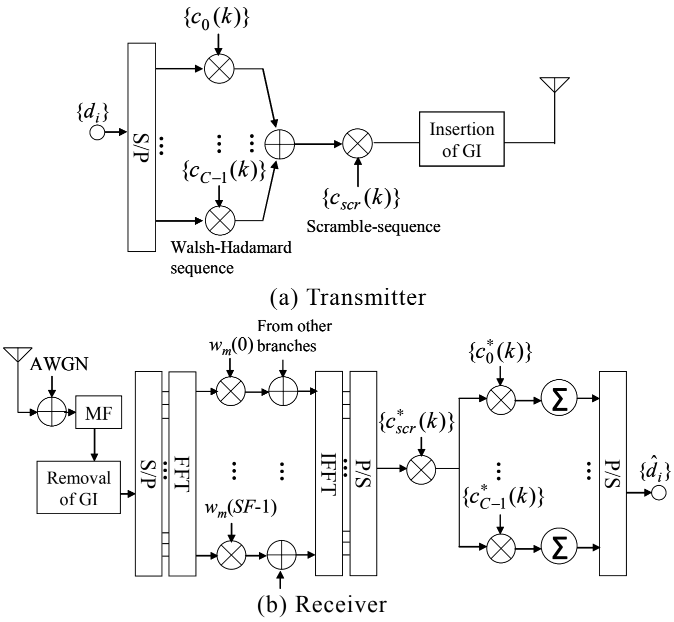


Fig. 1 Transmission system model

2.1. Insertion of Guard Interval (GI) for Frequency-domain Equalization

Fast Fourier transform (FFT) is applied for decomposing the received DS-CDMA signal into the SF subcarrier components (the term "subcarrier" is used although subcarriers are not used for data modulation) for frequency-domain equalization and antenna diversity combining. At the receiver, the received DS-CDMA signal with spreading factor SF on each diversity antenna is sampled at the chip rate. The FFT windowsize is equal to the spreading factor SF. For applying FFT, the received signal waveform must be treated as a periodic function in time with the repetition period of SF chips. Remembering that the wireless channel consists of many time delayed paths [2], cyclic extension of the transmitting waveform needs to be applied; a copy of the last part of N_g chips in the transmitting signal waveform is inserted into the beginning of the signal waveform as a guard interval (GI) as in MC-CDMA (see Fig. 2). The GI length T_g needs to be longer than the largest time delay difference in the channel. Letting T_c be the chip period, T_g is $T_g=T_cN_g$ and the effective symbol length is $T_s=T_cSF$. Then, GI-inserted DS-CDMA signaling period is $T=T_s+T_g$. Hence, the data symbol rate decreases by a factor of $(1+T_g/T_s)$ or $(1+N_g/SF)$ times compared to the no GI insertion system (which uses rake combining instead of frequency-domain equalization) and also power penalty of $(1+T_g/T_s)$ or $(1+N_g/SF)$ is produced.

After joint one-tap frequency-domain equalization and antenna diversity combining, the time-domain signal waveform is obtained by applying inverse FFT (IFFT) for data demodulation. Since the IFFT operation is the linear combination of all SF subcarrier components, the well-known frequency diversity effect can be attained in a frequency-selective fading channel.

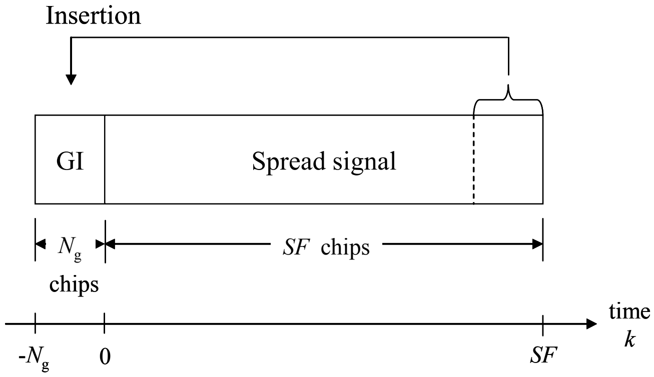


Fig. 2 Insertion of GI

2.2. Signal representation

For simplicity, we consider the 0th signaling interval, i.e., a time interval of $k=-N_g \sim SF-1$. At the transmitter, binary data sequence is transformed into quadrature phase shift keying (QPSK) symbol sequence $\{d_i;\ i=0 \sim C-1\}$, each symbol is then spread using orthogonal spreading codes $\{c_i(k)=\pm 1; i=0 \sim C-1, k=0 \sim SF-1\}$ of spreading factor SF. The resultant orthogonal C parallel chip sequences are added (i.e., code multiplexed) and then multiplied by a scramble sequence $\{c_{scr}(k)=\pm 1; k=\cdot\cdot,-1,0,1,\cdot\cdot\}$ for making the transmitting signal noise-like.

Throughout the paper, the chip-spaced discrete time representation is used. The generated multicode DS-CDMA signal waveform $s(k)$ can be expressed using the equivalent baseband representation as

$$s(k)=\sqrt{2E_c/T_c}\sum_{i=0}^{C-1} d_i c_i(k) c_{scr}(k), \quad k=0 \sim SF-1 \quad , (1)$$

where E_c represents the chip energy. The GI-inserted signal waveform can be expressed as

$$\tilde{s}(k)=s(k \bmod SF) \quad , \quad k=-N_g \sim SF-1 \quad , \quad (2)$$

which is transmitted over a frequency-selective fading channel and received by M antennas at the receiver.

The channel is assumed to be composed of L distinct propagation paths with different time delays. The complex path gain and time delay of the lth path corresponding to the mth antenna are respectively denoted by $\xi_{m,l}$ and τ_l. The signal waveform received on the mth antenna at time k may be expressed as

$$r_m(k)=\sum_{l=0}^{L-1}\xi_{m,l}\tilde{s}(k-\frac{\tau_l}{T_c})+\eta_m(k) \quad , \quad (3)$$

where $\{\eta_m(k)\}$ is the zero-mean complex Gaussian process with variance $2N_0/T_c$ due to the additive white Gaussian noise (AWGN) having the one-sided power spectrum density N_0. Block fading, where the path gains stay constant over one signaling period, is assumed. After removal of GI, the received signal is decomposed into SF subcarrier components $\{R_m(n); n=0 \sim SF-1\}$ by applying SF-point FFT. $R_m(n)$ is given by

$$\begin{aligned} R_m(n) &= \sum_{k=0}^{SF-1} r_m(k)\exp(-j2\pi n\frac{k}{SF}) \\ &= H_m(n)S(n)+\tilde{\eta}_m(n) \end{aligned} \quad , (4)$$

where $H_m(n)$ and $S(n)$ are the Fourier transforms of the channel impulse response and the transmitted multicode DS-CDMA signal waveform, respectively. In Eq.(4), $\tilde{\eta}_m(n)$ represents the noise component at the nth subcarrier frequency. $R_m(n)$ is multiplied by the weight $w_m(n)$ for joint frequency-domain equalization and antenna diversity combining to obtain

$$\tilde{R}(n)=\sum_{m=0}^{M-1} R_m(n) w_m(n)\ . \ (5)$$

The time-domain signal waveform $\{\tilde{r}(k)\}$ obtained by SF-point IFFT is given by

$$\tilde{r}(k)=\frac{1}{SF}\sum_{n=0}^{SF-1}\tilde{R}(n)\exp(j2\pi k\frac{n}{SF}) \quad . \quad (6)$$

Parallel despreading and descrambling operation is performed on $\{\tilde{r}(k)\}$ to obtain the soft decision sample sequence $\{\hat{d}_i\}$:

$$\hat{d}_i=\frac{1}{SF}\sum_{k=0}^{SF-1}\tilde{r}(k)c_i^*(k)c_{scr}^*(k) \quad , \quad i=0 \sim C-1 \qquad (7)$$

for succeeding data demodulation.

2.3. Weights for joint frequency-domain equalization and antenna diversity combining

In this paper, a heuristic approach is taken following the frequency-domain equalization used in MC-CDMA. Various frequency-domain equalization schemes using MRC, EGC, ORC and MMSEC are considered to compare the achievable BER performance in a frequency-selective fading channel. Joint frequency-domain equalization and diversity combining weight described in [9] can be used:

$$w_m(n)=\begin{cases} H_m^*(n), & \text{MRC} \\ \dfrac{H_m^*(n)}{|H_m(n)|}, & \text{EGC} \\ \dfrac{H_m^*(n)}{\sum_{m=0}^{M-1}|H_m(n)|^2}, & \text{ORC} \\ \dfrac{H_m^*(n)}{\sum_{m=0}^{M-1}|H_m(n)|^2+\left(C\dfrac{E_c}{N_0}\right)^{-1}}, & \text{MMSEC} \end{cases} \quad ,(8)$$

where E_c/N_0 represents the average received chip energy-to-AWGN power spectrum density ratio. The nth subcarrier component $\widetilde{R}(n)$ of Eq. (5) after joint frequency-domain equalization and antenna diversity combining is now rewritten as

$$\begin{aligned}\widetilde{R}(n)&=\left(\sum_{m=0}^{M-1}w_m(n)H_m(n)\right)S(n)+\sum_{m=0}^{M-1}w_m(n)\widetilde{\eta}_m(n)\\ &=\widetilde{H}(n)S(n)+\widetilde{\eta}'(n)\end{aligned} \quad , (9)$$

where the first term is the signal component and the second the noise component. ORC can completely restore the frequency nonselective channel (thus, orthogonality of spreading codes can be restored) but produces noise enhancement. Restoration of frequency non-selectivity and noise enhancement have a trade-off relationship. MMSEC cannot completely restore the frequency non-selectivity but minimizes the equalization error on each subcarrier.

3. Computer Simulation

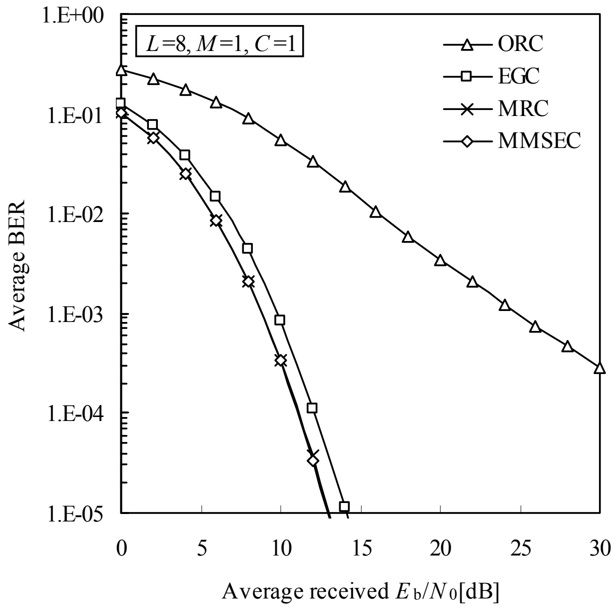
Simulation condition is shown in Table 1. A very slow L-path frequency-selective block Rayleigh fading channel having uniform power delay profile is assumed. The time delay τ_l of the lth path is assumed to be $\tau_l = lT_c$.

Table 1 Simulation condition

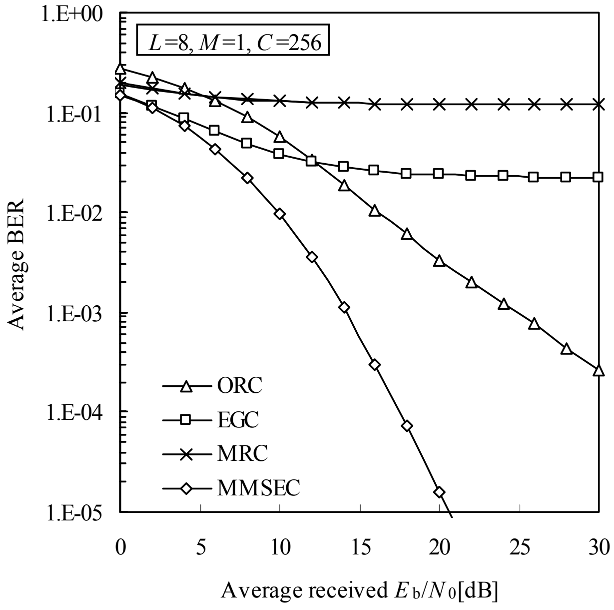
Data modulation		QPSK
Multicode spreading	Spreading modulation	BPSK
	Spreading factor	SF=256
	No. parallel codes	C=1~256
Scramble code		M-sequence with a period of 4095 chips
Guard interval		$T_g=32T_c$
Propagation channel model		Block Rayleigh fading channel with L=1~32 paths
No. of FFT samples		256 (=SF)
No. of antennas		M=1~4
Frequency-domain equalization		ORC, EGC, MRC, MMSEC
Channel estimation		Ideal

3.1. Frequency-domain ORC, EGC, MRC, and MMSEC equalizations

The average BER performances with frequency-domain ORC, EGC, MRC, and MMSEC equalizations are plotted as a function of the average received signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0 in Fig. 3 for various values of C in the case of L=8 and M=1. E_b/N_0 is defined as $E_b/N_0=(SF+N_g)E_c/N_0$. The MRC and EGC can achieve the frequency diversity effect and there is no noise enhancement. Hence, they provide very good BER performances. However, this is only true for the single code case (C=1). For the multicode case, the BER performances of EGC and MRC degrade and the BER floors are seen due to enhanced frequency-selectivity of the channel (the MRC performance is much worse than the EGC performance). On the other hand, the BER performance of ORC is insensitive to the value of C because of perfect restoration of frequency-nonselectivity, but its BER performance is even worse than those of EGC and MRC for low code-multiplexing order. This suggests that MMSEC can only be used for frequency-domain equalization of DS-CDMA signals. It can be clearly seen in Fig. 3(b) that the MMSEC always provides the best BER performance among the four equalization schemes. Hence, in the following simulation, only MMSEC is considered.



(a) C=1



(b) C=256

Fig. 3 Performance comparison of frequency-domain ORC, EGC, MRC, and MMSEC equalizations for L=8 and M=1.

3.2. Performance comparison of frequency-domain MMSEC equalization and rake combining

Performance comparison of frequency-domain MMSEC equalization and rake combining for multicode case is illustrated in Fig. 4. As C increases, the BER performance with rake combining significantly degrades due to increasing inter-code interference (ICI) resulting from IPI and hence BER floors appear. However, the BER performance with frequency-domain MMSEC equalization provides much better BER performance due to the frequency diversity effect and no BER floor is present at the cost of slightly reduced data rate and power penalty.

So far, we have assumed L=8. How the number of propagation paths impacts the required E_b/N_0 for BER=10^{-4} with frequency-domain MMSEC equalization is plotted in Fig. 5 for M=1, 2, and 4. It is clearly seen that as L increases, the channel frequency-selectivity becomes stronger and increased frequency diversity effect can be obtained, thereby improving the BER performance with frequency-domain MMSEC equalization as in the case of MC-CDMA. The frequency diversity gain is defined here as the reduced value in dB of the required E_b/N_0 compared to the L=1 case. The frequency diversity gain of as large as about 25 (19) dB is obtained for C=1 (256) when L=32 and M=1, respectively. Although the frequency diversity gain becomes smaller as M increases, a gain of 4.7(3.5) dB can still be achieved for C=1(256) when M=4.

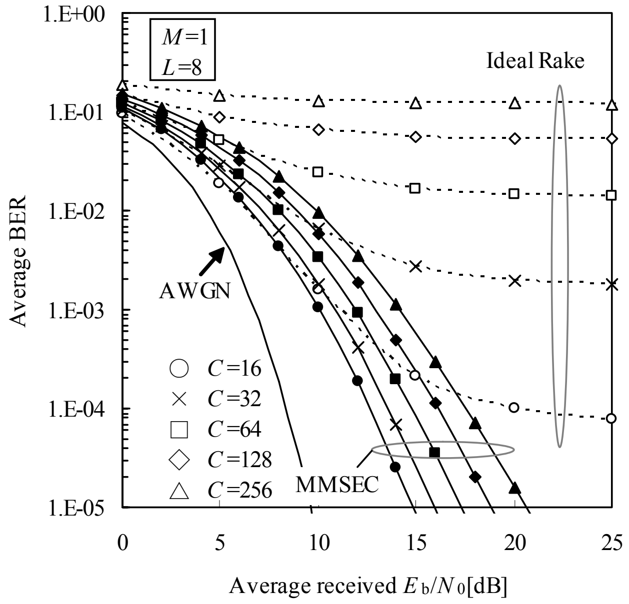


Fig. 4 Performance comparison between frequency-domain MMSEC equalization and rake combining for multicode case. L=8.

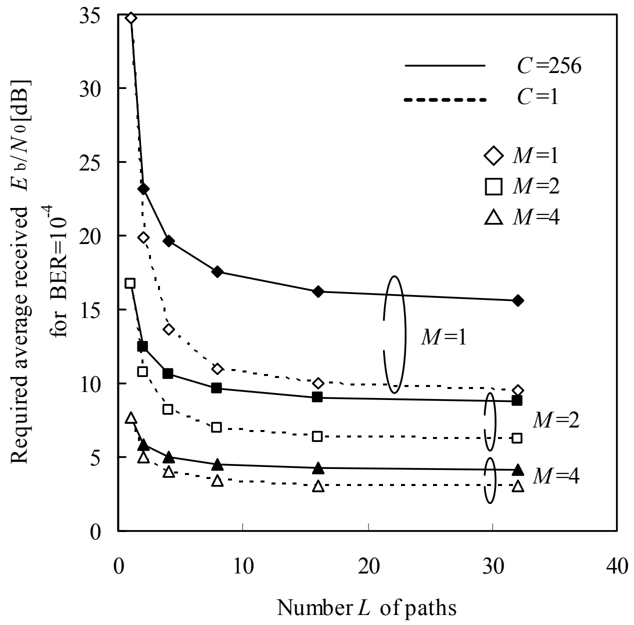


Fig. 5 Impact of number L of paths.

3.3. Performance comparison of DS-CDMA and MC-CDMA

It is interesting to compare the DS-CDMA performance with MC-CDMA. Figure 6 illustrates the BER performances with DS-CDMA and MC-CDMA both using frequency-domain MMSEC equalization for the same transmission condition, i.e., the same data rate and the same spreading factor (spreading bandwidth), for an L=8-path frequency-selective channel and no antenna diversity (M=1). Also plotted is the result of OFDM using 256 subcarriers and the same data rate. It is clearly seen that both DS-CDMA and MC-CDMA with frequency-domain

MMSEC equalization can achieve almost the identical BER performance because the same frequency diversity effect is obtained.

Figure 7 shows how antenna diversity improves the BER performance for C=1 and 256. As the number M of antennas increases, the BER performances of both DS-CDMA and MC-CDMA with frequency-domain MMSEC equalization consistently improves. Again there is no performance difference between DS-CDMA and MC-CDMA. When M=4, the BER=10^{-4} can be achieved at the average E_b/N_0 of as small as 5dB even for C=256.

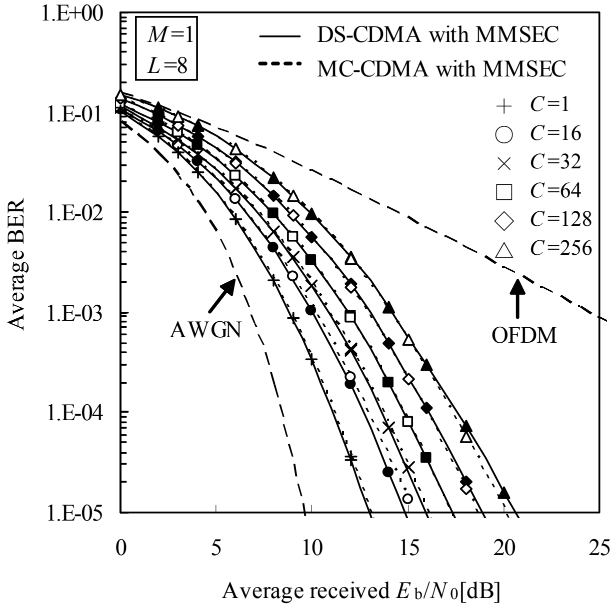


Fig. 6 Performance comparison of DS-CDMA and MC-CDMA both using frequency-domain MMSEC equalization for no antenna diversity (M=1). L=8.

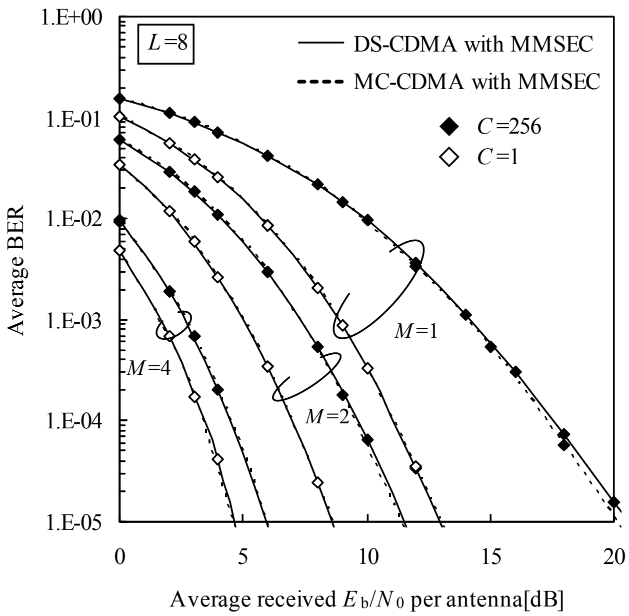


Fig. 7 Performance comparison of DS-CDMA and MC-CDMA both using frequency-domain MMSEC equalization when antenna diversity is used. L=8.

4. Conclusion

In this paper, joint use of frequency-domain equalization and antenna diversity combining was considered for improving the DS-CDMA signal transmission performance in a frequency selective fading channel and the achievable BER performance was evaluated by computer simulation. In the case of rake combining, as the number C of codes increases, the BER performance with rake combining significantly degrades and BER floors appear due to increasing IPI. However, the BER performance with frequency-domain MMSEC equalization provides much better BER performance due to the frequency diversity effect and produces no BER floors at the cost of slightly reduced data rate and power penalty. It was shown that both DS-CDMA and MC-CDMA with frequency-domain MMSEC equalization can achieve almost identical BER performance for any number of diversity antennas.

In this paper, ideal channel estimation was assumed. Pilot assisted channel estimation can be applied to estimate the channel gains. Pilot sequence design and the evaluation of the BER performance using a practical channel estimation method is left for an interesting future study.

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