PAPER

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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SUMMARY Orthogonal multicode direct sequence code division multiple access (DS-CDMA) has the flexibility in offering various data rate services. However, in a frequency-selective fading channel, the bit error rate (BER) performance is severely degraded since the 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 orthogonal multicode 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.

key words: *frequency-domain equalization, antenna diversity, multicode DS-CDMA, frequency-selective fading*

1. Introduction

In mobile radio communications systems, bit error rate (BER) performance of high-speed data transmission may be severely degraded due to frequency-selective multipath fading resulting from the presence of many propagation paths with different time delays [1]. In direct sequence code division multiple access (DS-CDMA), the multipath fading channel is resolved by a bank of correlators (known as the rake fingers) into many distinct paths with different time delays 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 combining) [2]. 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 obtainable by rake combining. Antenna diversity combining is one of the effective techniques to improve the BER performance of multicode DS-CDMA as well as rake combining. But it has been found by authors' computer simulation that in a severe frequency-selective channel, even if rake combining and antenna diversity combining are jointly used, a good BER performance cannot be obtained due to the destruction of code orthogonality resulting from severe IPI (this is discussed in Sect. 3.2).

Recently, multi-carrier CDMA (MC-CDMA) has been attracting much attention for wireless multiple access in a severe frequency-selective fading channel [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 (MC-CDMA applies frequency-domain spreading while DS-CDMA applies time-domain spreading). 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]. Meanwhile, application of frequency-domain equalization to single-carrier (SC) transmission has been attracting attention [6].

Orthogonal multicode DS-CDMA has the flexibility in offering various data rate services by changing the number of parallel orthogonal spreading codes [3]. 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. 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. The code orthogonality is partially restored by frequency-domain equalization. This implies that unlike the case of rake combining, further performance improvement can be expected by jointly using frequency-domain equalization and antenna diversity combining. In this paper, the joint use of frequency-domain equalization per subcarrier and antenna diversity combining is proposed for multicode DS-CDMA. The remainder of this paper is organized as follows. Section 2 presents the 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 to show that frequency-domain MMSEC equalization provides the best BER performance than others. How the antenna diversity combining improves the

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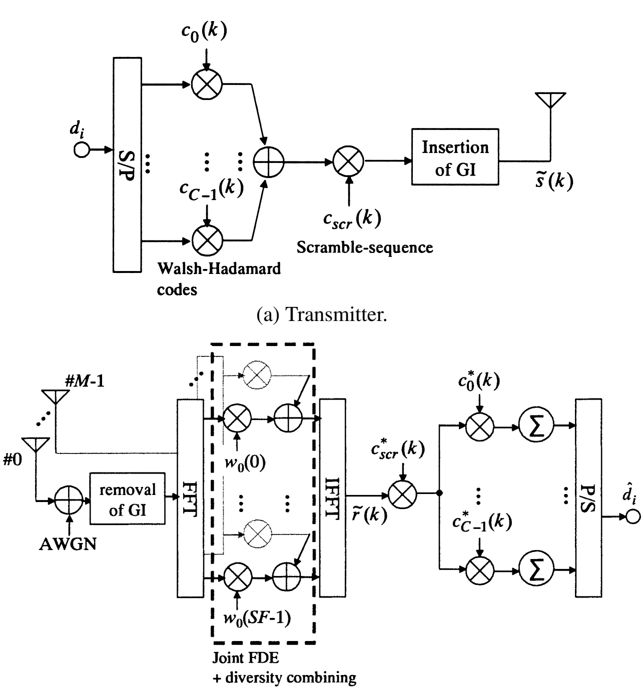
achievable BER performance and how the number of resolvable paths affects the BER performance are discussed. Some conclusions and future work are offered in Sect. 4.

2. Joint Frequency-Domain Equalization and Antenna Diversity Combining

The presence of many propagation paths with different time delays produces a severe frequency-selective channel (i.e., the channel transfer function is not anymore constant but a complicated function of frequency) and hence, the received signal is distorted. Thus, some form of equalization is necessary. In this paper, frequency-domain equalization per subcarrier (i.e., multiplying the equalization weight to each subcarrier component obtained by performing fast Fourier transform (FFT) to the received signal) is considered. Note that in this paper, the term "subcarrier" is used for convenience although subcarriers are not used for data modulation. Antenna diversity combining is a technique to combine multiple copies of the same signal, which are received using spatially separated antennas, and can reduce the adverse effect of fading. Jointly performing frequency-domain equalization and antenna diversity combining can further improve the BER performance of orthogonal multicode DS-CDMA.

2.1 Transmission System Model

The transmission system model of orthogonal multicode DS-CDMA using frequency-domain equalization and antenna diversity combining is illustrated in Fig. 1. Transmission process is explained using mathematical expressions of the signals. Throughout the paper, the chip-spaced discrete



(a) Transmitter.

(b) Receiver.

Fig. 1 Transmission system model.

time representation is used with k representing the time index.

At the transmitter, a binary data sequence is transformed into data-modulated symbol sequence and then serial-to-parallel (S/P) converted into C parallel symbol streams. Without loss of generality, it is assumed that C data symbols $\{d_i;\ i = 0 \sim C-1\}$ are transmitted. Each symbol is then spread using one of C orthogonal spreading codes $\{c_i(k);\ i = 0 \sim C-1,\ k = 0 \sim SF-1\}$, where SF represents the spreading factor. The resultant C parallel chip sequences are added (i.e., code-multiplexed) and multiplied by a scramble sequence $\{c_{scr}(k);\ k = 0 \sim SF-1\}$ for making the transmit orthogonal multicode DS-CDMA signal noise-like.

Since the propagation channel consists of many distinct paths having different time delays, cyclic extension of the transmit waveform needs to be added for FFT operation at the receiver. The last part of N_g chips in the transmit signal waveform of SF chips is copied as a cyclic extension and is inserted into the guard interval (GI) placed at the beginning of the signal waveform as in MC-CDMA [7]. The GI length needs to be longer than the largest time delay difference in the channel. Then, the GI-inserted orthogonal multicode DS-CDMA signal $\{\tilde{s}(k);\ k = -N_g \sim SF-1\}$ is transmitted.

At the receiver, M diversity antennas are used. The orthogonal multicode DS-CDMA signal $\{r_m(k);\ k = -N_g \sim SF-1\}$ received by the mth diversity antenna is sampled at the chip rate. After the removal of GI, FFT is applied for decomposing the received orthogonal multicode DS-CDMA signal into the SF subcarrier components (the number of FFT samples is equal to SF) for frequency-domain equalization and antenna diversity combining. Each subcarrier component is multiplied by the weight $\{w_m(n);\ n = 0 \sim SF-1\}$ for joint frequency-domain equalization and antenna diversity combining, where n is the subcarrier index. Then, antenna diversity combining is performed at each subcarrier. After joint frequency-domain equalization and antenna diversity combining, the time-domain signal $\{\tilde{r}(k);\ k = 0 \sim SF-1\}$ is obtained by inverse FFT (IFFT). Since the IFFT operation is a linear combination of all SF subcarrier components, frequency diversity effect can be achieved in a frequency-selective fading channel. Finally, descrambling and parallel despreading operations are performed using $c^*_{scr}(k)$ and $\{c^*_i(k);\ i = 0 \sim C-1\}$ for data demodulation.

2.2 Signal Representation

As in Sect. 2.1, we consider the transmission of the C symbols during the time interval of $k = -N_g \sim SF-1$. The GI-inserted orthogonal multicode DS-CDMA signal waveform $\tilde{s}(k)$ can be expressed using the equivalent baseband representation as

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

where $s(k)$ is given by

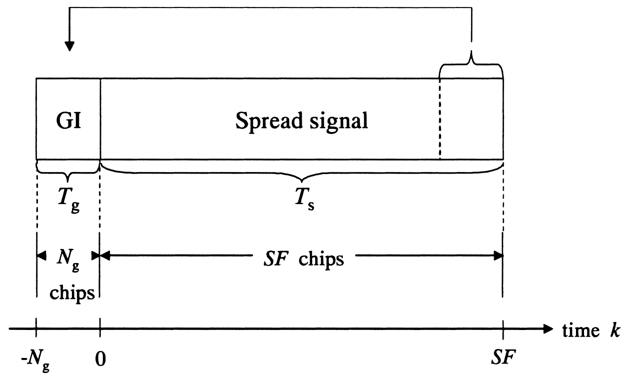


Fig. 2 Insertion of GI.

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

with E_c representing the chip energy. $\tilde{s}(k)$ is transmitted and received at the receiver by M antennas. Figure 2 illustrates the transmit signal $\tilde{s}(k)$ after GI insertion. The GI length T_g and the effective symbol length T_s are respectively given by $T_g = T_c N_g$ and $T_s = T_c SF$, where T_c is the chip period and thus, the GI-inserted orthogonal multicode DS-CDMA signal period T is given by $T = T_s + T_g$. Hence, the data symbol rate decreases by a factor of $(1+T_g/T_s)$ or $(1+N_g/SF)$ times compared to that of rake combining (no GI insertion is necessary) and a power penalty of $(1+T_g/T_s)$ or $(1+N_g/SF)$ is also produced.

Let the channel be composed of L distinct propagation paths with different time delays. Let the complex path gain and time delay of the lth path corresponding to the mth antenna be denoted by $\xi_{m,l}$ and τ_l chips, respectively, where $\sum_{l=0}^{L-1} E[|\xi_{m,l}|^2] = 1$ with $E[.]$ being the ensemble average operation. The signal waveform received on the mth antenna at time k is expressed as

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

where $\eta_m(k)$ is the zero-mean Gaussian process with a variance $2N_0/T_c$ due to an additive white Gaussian noise (AWGN) having a one-sided power spectrum density N_0. Block fading, where the path gains stay constant over the time interval of $k = -N_g SF - 1$, is assumed. After the 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

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

where $H_m(n)$ and $S(n)$ are the Fourier transforms of the channel impulse response and the transmitted orthogonal multicode DS-CDMA signal waveform, respectively, and are given by

$$\begin{cases} H_m(n) = \displaystyle\sum_{l=0}^{L-1} \xi_{m,l}\exp\left(-j2\pi\tau_l\frac{n}{SF}\right) \\ S(n) = \displaystyle\sum_{k=0}^{SF-1} s(k)\exp\left(-j2\pi k\frac{n}{SF}\right) \end{cases}. \tag{5}$$

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

$$\tilde{R}(n) = \sum_{m=0}^{M-1} R_m(n)w_m(n). \tag{6}$$

The time-domain signal waveform $\{\tilde{r}(k);\ k = 0 \sim SF-1\}$ obtained by IFFT is given by

$$\tilde{r}(k) = \frac{1}{SF}\sum_{n=0}^{SF-1}\tilde{R}(n)\exp\left(j2\pi k\frac{n}{SF}\right). \tag{7}$$

Descrambling and parallel despreading operations are performed on $\tilde{r}(k)$ to obtain the soft decision sample sequence $\{\hat{d}_i;\ i = 0 \sim C-1\}$:

$$\hat{d}_i = \frac{1}{SF}\sum_{k=0}^{SF-1}\tilde{r}(k)c_i^*(k)c_{scr}^*(k), \quad i = 0 \sim C-1 \tag{8}$$

for 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. ORC can completely restore the frequency-nonselective channel (thus, perfect 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-nonselectivity but minimizes the equalization error on each subcarrier.

Joint frequency-domain equalization and antenna diversity combining weight described in [9] can be used:

$$w_m(n) = \begin{cases} H_m^*(n), & \text{MRC} \\ \dfrac{H_m^*(n)}{|H_m(n)|}, & \text{EGC} \\ \dfrac{H_m^*(n)}{\sum_{m=0}^{M-1}|H_m(n)|^2}, & \text{ORC} \\ \dfrac{H_m^*(n)}{\sum_{m=0}^{M-1}|H_m(n)|^2 + \left(C\dfrac{E_c}{N_0}\right)^{-1}}, & \text{MMSEC,} \end{cases} \tag{9}$$

where E_c/N_0 represents the average received chip energy-to-AWGN power spectrum density ratio.

The nth subcarrier component $\tilde{R}(n)$ of Eq. (6) after joint frequency-domain equalization and antenna diversity combining is now rewritten as

$$\begin{aligned}\tilde{R}(n) &= \left(\sum_{m=0}^{M-1} w_m(n)H_m(n)\right)S(n) + \sum_{m=0}^{M-1} w_m(n)\tilde{\eta}_m(n)\\ &= \tilde{H}(n)S(n) + \tilde{\eta}'(n), \end{aligned}\qquad (10)$$

where the first term is the signal component and the second is the noise component. Comparison of Eqs. (4) and (10) shows that $\tilde{H}(n)$ and $\tilde{\eta}'(n)$ represent the channel gain and noise after joint frequency-domain equalization and antenna diversity combining, respectively. One shot observations of $|w_0(n)|$, $\left|\tilde{H}(n)\right|$ $(= |w_0(n)H_0(n)|)$ and $\tilde{\eta}'(n)$ $(= w_0(n)\tilde{\eta}_0(n))$ are presented for no antenna diversity (M=1) and L=3-path channel in Appendix.

3. Computer Simulation

Simulation conditions are shown in Table 1. An L-path frequency-selective block Rayleigh fading channel having uniform power delay profile (i.e., $E[|\xi_{m,l}|^2] = 1/L$ for all m and l) is assumed. The time delay τ_l of the lth path is assumed to be $\tau_l = l$ chips.

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 when L=8 and M=1, where E_b/N_0 is defined as $E_b/N_0 = (SF + N_g)E_c/N_0$. Since each data symbol is spread over all SF subcarriers, frequency-nonselectivity must be restored, otherwise the BER performance significantly degrades. This suggests that only ORC and MMSEC can be used for frequency-domain equalization of DS-CDMA signals. It can be clearly seen in Fig. 3 that the MMSEC always provides the best BER performance among the four equalization schemes. 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, e.g., $C \leq 16$.

Figure 4 compares the BER performances achievable by ORC and MMSEC with antenna diversity combining. It can be seen that the MMSEC always provides better BER performance than ORC although the performance difference becomes smaller as the number M of antennas increases. Hence, in the following simulation, only MMSEC is considered.

3.2 Performance Comparison of Frequency-Domain MMSEC Equalization and Rake Combining

Firstly, the BER performance with frequency-domain MMSEC equalization is compared with that of rake combining for the single-code case (C=1) in Fig. 5. As L increases, the frequency-selectivity of the channel becomes stronger and

Table 1 Simulation condition.

Data modulation		QPSK
Multicode spreading	Spreading modulation	BPSK
	Spreading factor	SF=256
	No. of parallel codes	C=1~256
Scramble code		M-sequence with a period of 4095 chips
Guard interval		T_g=32 chips
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

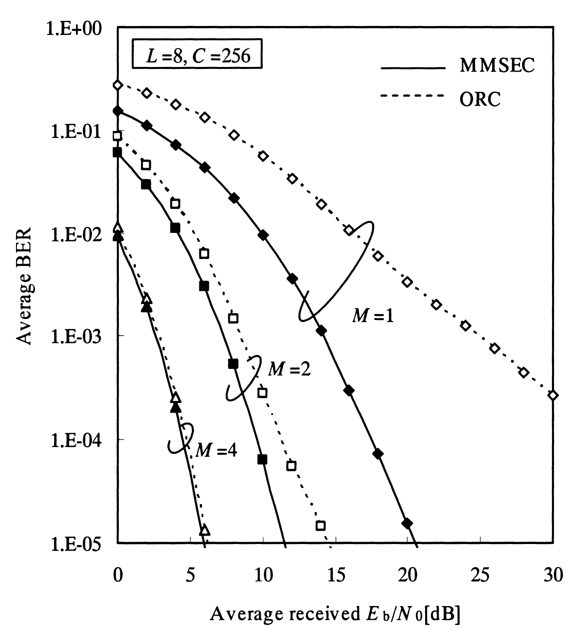
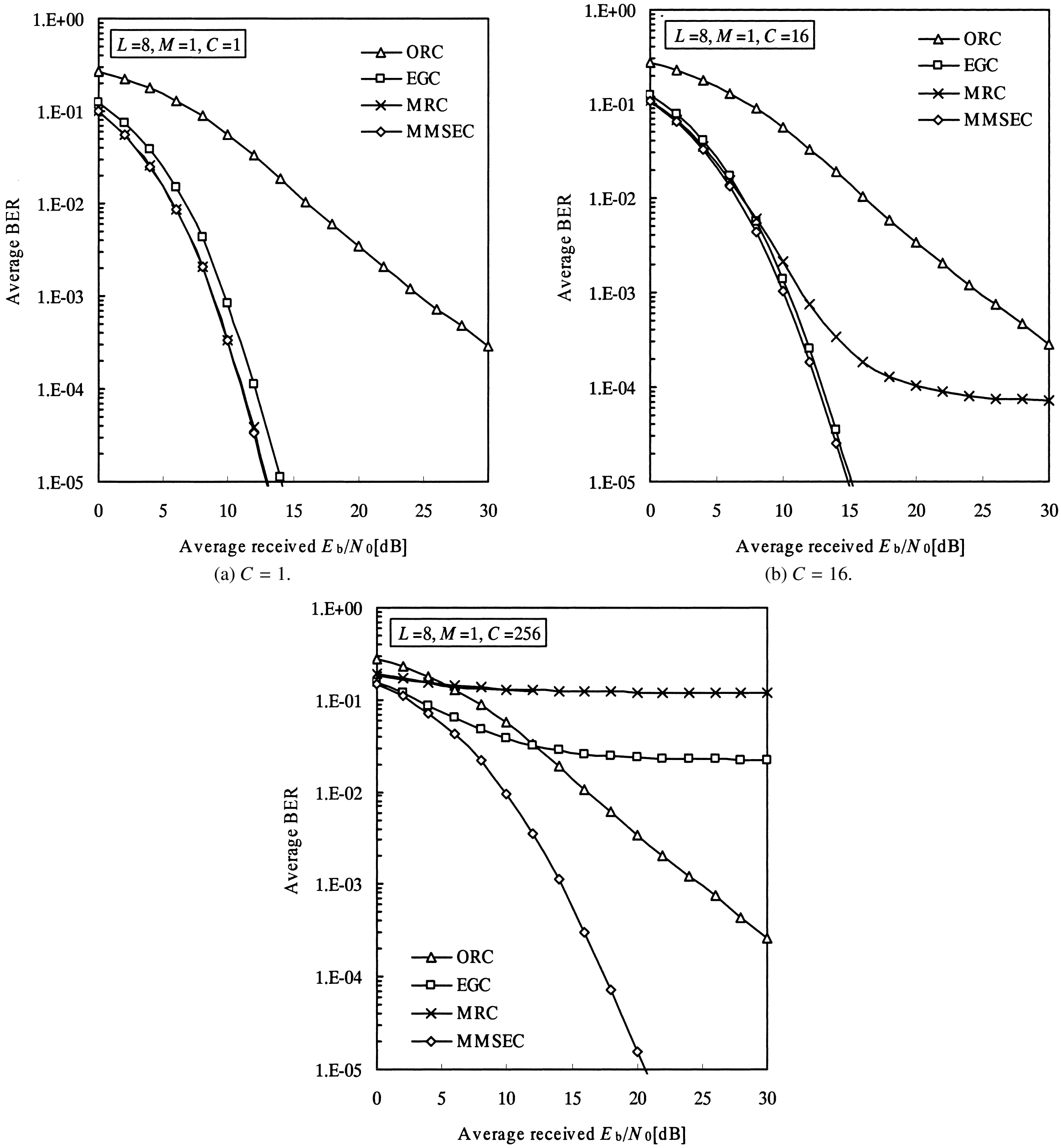


Fig. 4 Performance comparison of frequency-domain ORC and MMSEC equalizations with antenna diversity reception for L=8 and C=256.



(a) C = 1.

(b) C = 16.

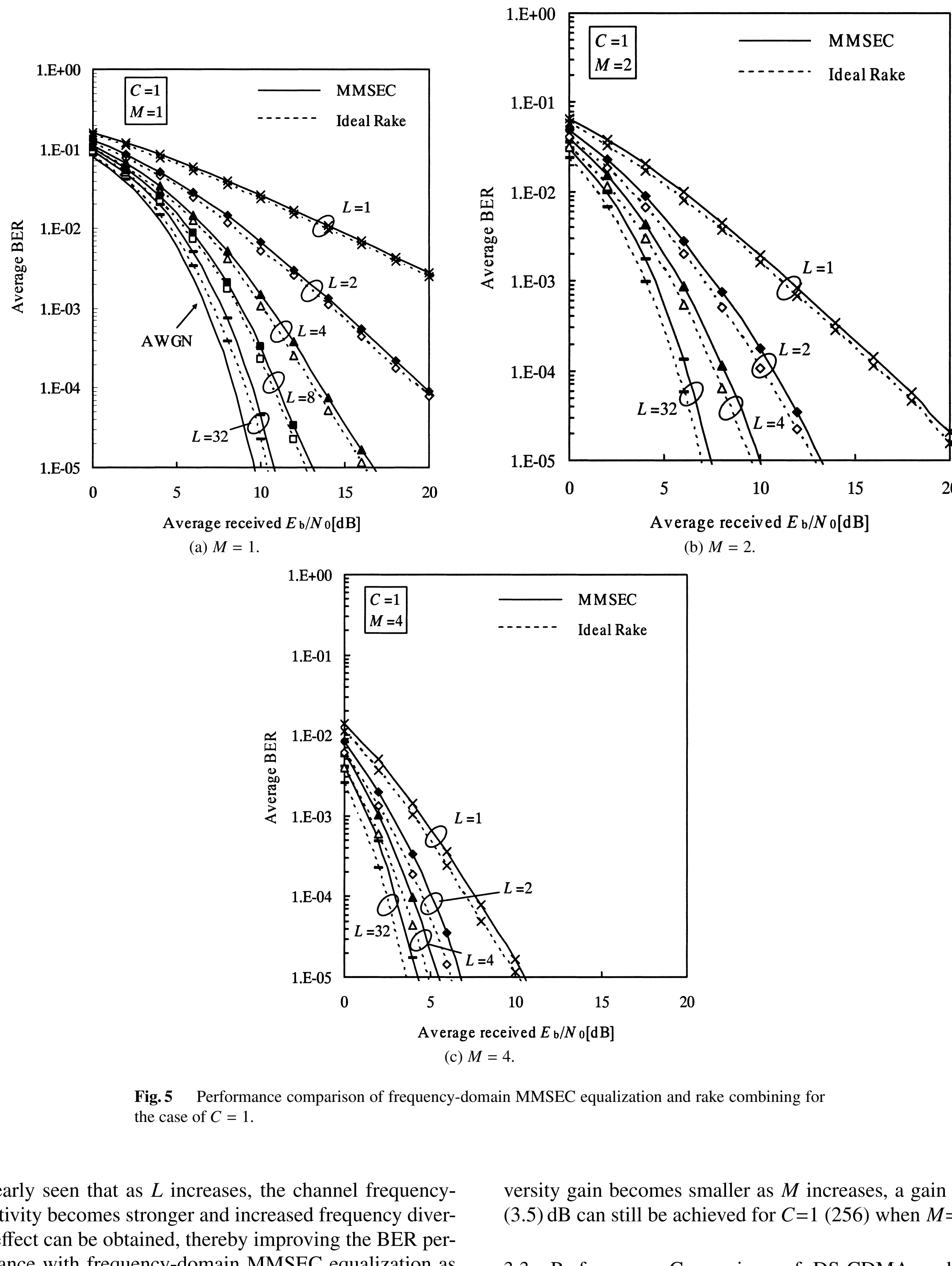
(c) C = 256.

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

hence, the BER performance with frequency-domain MMSEC equalization improves due to the increase in the frequency diversity effect and approaches that of AWGN channel. Since the spreading factor of SF=256 is large enough, IPI is negligible and hence, the BER performance with rake combining also improves as L increases. The data rate for frequency-domain MMSEC equalization is 8/9 times that of rake combining and frequency-domain MMSEC equalization has only a 0.5 dB performance loss due to the power penalty of 0.5 dB compared to rake combining.

Performance comparison of frequency-domain MMSEC equalization and rake combining for multicode case is illustrated in Fig. 6. An L=8-path channel is assumed. 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.

The impact of the number of propagation paths on the required E_b/N_0 for BER=10^{-4} with frequency-domain MMSEC equalization is plotted in Fig. 7 for M=1, 2, and 4. It



(a) M = 1.

(b) M = 2.

(c) M = 4.

Fig. 5 Performance comparison of frequency-domain MMSEC equalization and rake combining for the case of C = 1.

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 25.2 (19.2) dB is obtained for C=1(256)when L=32 and M=1. 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.

3.3 Performance Comparison of DS-CDMA and MC-CDMA

It is interesting to compare the DS-CDMA performance with MC-CDMA. Figure 8 illustrates the BER performances with DS-CDMA and MC-CDMA both using frequency-

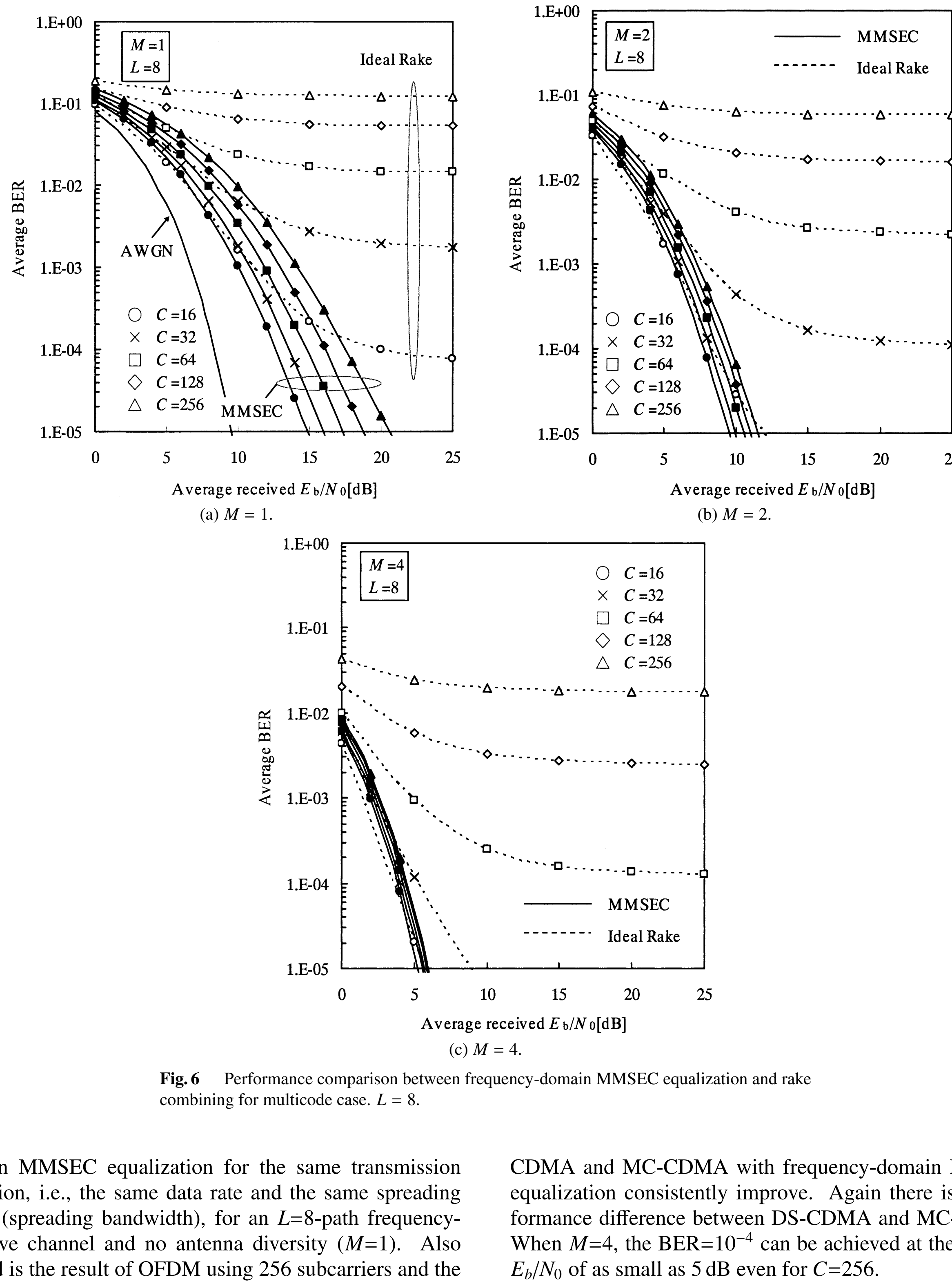


Fig. 6 Performance comparison between frequency-domain MMSEC equalization and rake combining for multicode case. $L = 8$.

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 identical BER performance because the same frequency diversity effect is obtained.

Figure 9 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 improve. 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 5 dB even for C=256.

4. Conclusion

In this paper, joint use of frequency-domain equalization and antenna diversity combining was considered for improving the orthogonal multicode DS-CDMA signal transmission performance in a frequency-selective fading chan-

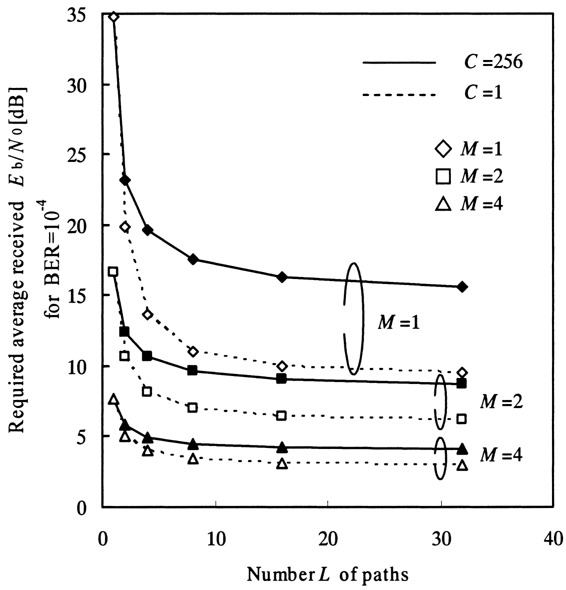


Fig. 7 Impact of number L of paths.

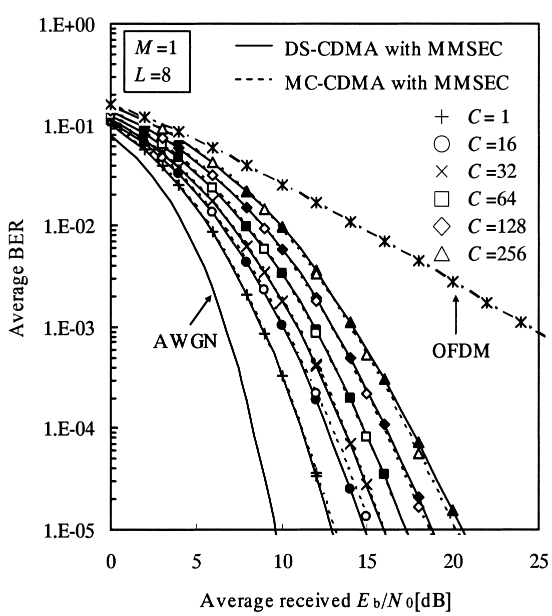


Fig. 8 Performance comparison of DS-CDMA and MC-CDMA both using frequency-domain MMSEC equalization for no antenna diversity (M=1). L=8.

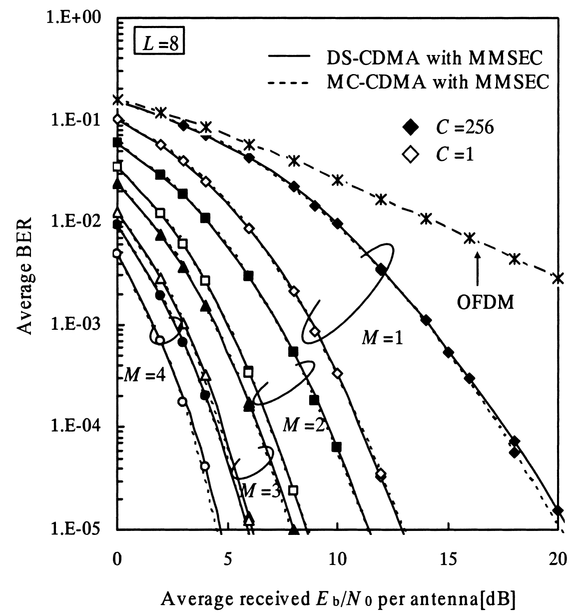


Fig. 9 Performance comparison of DS-CDMA and MC-CDMA both using frequency-domain MMSEC equalization when antenna diversity is used. L=8.

nel and the achievable BER performance was evaluated by computer simulation. In the case of rake combining, as the code multiplexing order C increases, the BER performance significantly degrades and BER floors appear due to increasing IPI. However, the 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. In addition, 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. Pilot sequence design and the evaluation of the BER performance using a practical channel estimation method is left for an interesting future study.

References

[1] W.C. Jakes, Jr., ed., Microwave mobile communications, Wiley, New York, 1974.

[2] F. Adachi, M. Sawahashi, and H. Suda, "Wideband DS-CDMA for next generation mobile communications systems," IEEE Commun. Mag., vol.36, no.9, pp.56–69, Sept. 1998.

[3] F. Adachi, K. Ohno, A. Higashi, and Y. Okumura, "Coherent multicode DS-CDMA mobile radio access," IEICE Trans. Commun., vol.E79-B, no.9, pp.1316–1325, Sept. 1996.

[4] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Commun. Mag., vol.35, no.12, pp.126–144, Dec. 1997.

[5] T. Sao and F. Adachi, "Comparative study of various frequency equalization techniques for downlink of a wireless OFDM-CDMA system," IEICE Trans. Commun., vol.E86-B, no.1, pp.352–364, Jan. 2003.

[6] D. Falconer, S.L. Ariyavistakul, A. Benyamin-Seeyer, and B. Eidson, "Frequency-domain equalization for single-carrier broadband wireless systems," IEEE Commun. Mag., vol.40, no.4, pp.58–66, April 2002.

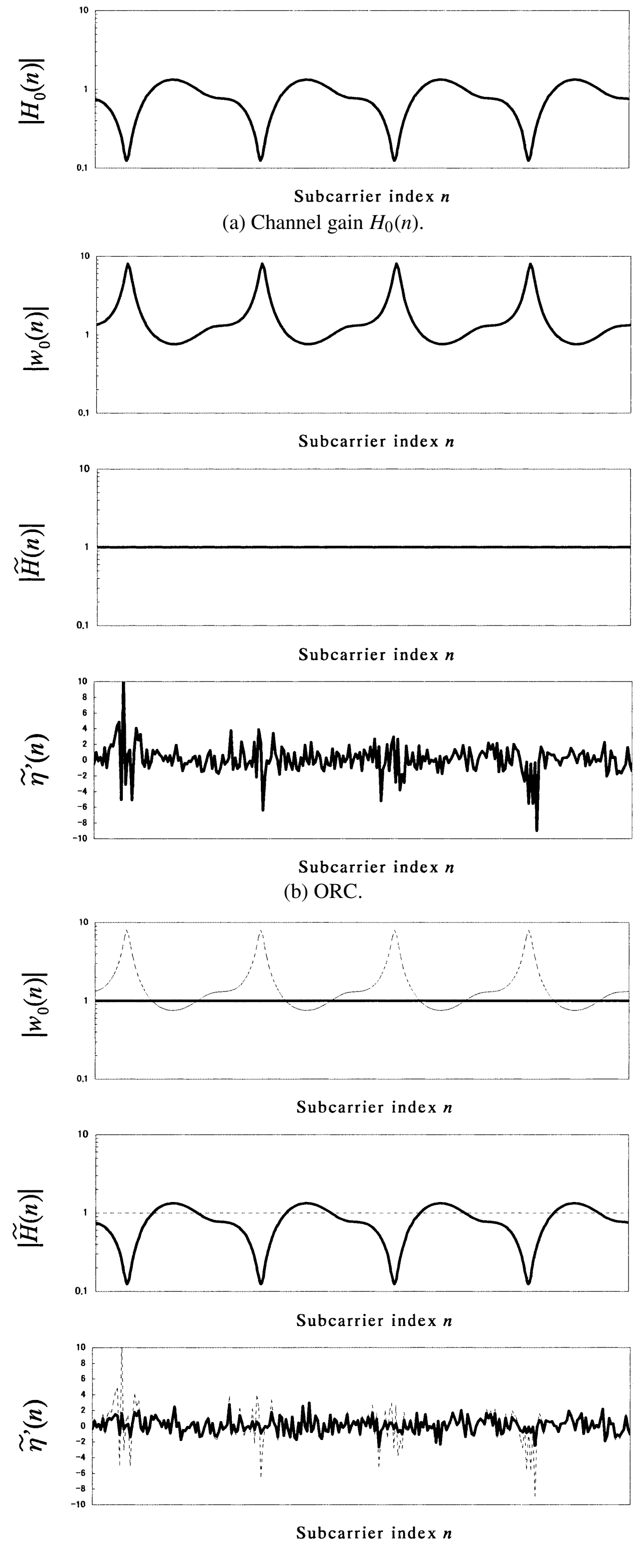
[7] F. Adachi, T. Sao, and T. Itagaki, "Performance of multicode DS-CDMA using frequency domain equalisation in frequency selective fading channel," Electron. Lett., vol.39, no.2, pp.239–241, Jan. 2003.

[8] A. Chouly, A. Brajal, and S. Jourdan, "Orthgonal multicarrier techniques applied to direct sequence spread spectrum CDMA system," Proc. IEEE Globecom'93, pp.1723–1728, Nov. 1993.

[9] F. Adachi and T. Sao, "Joint antenna diversity and frequency-domain equalization for multi-rate MC-CDMA," IEICE Trans. Commun., vol.E86-B, no.11, pp.3217–3224, Nov. 2003.

Appendix

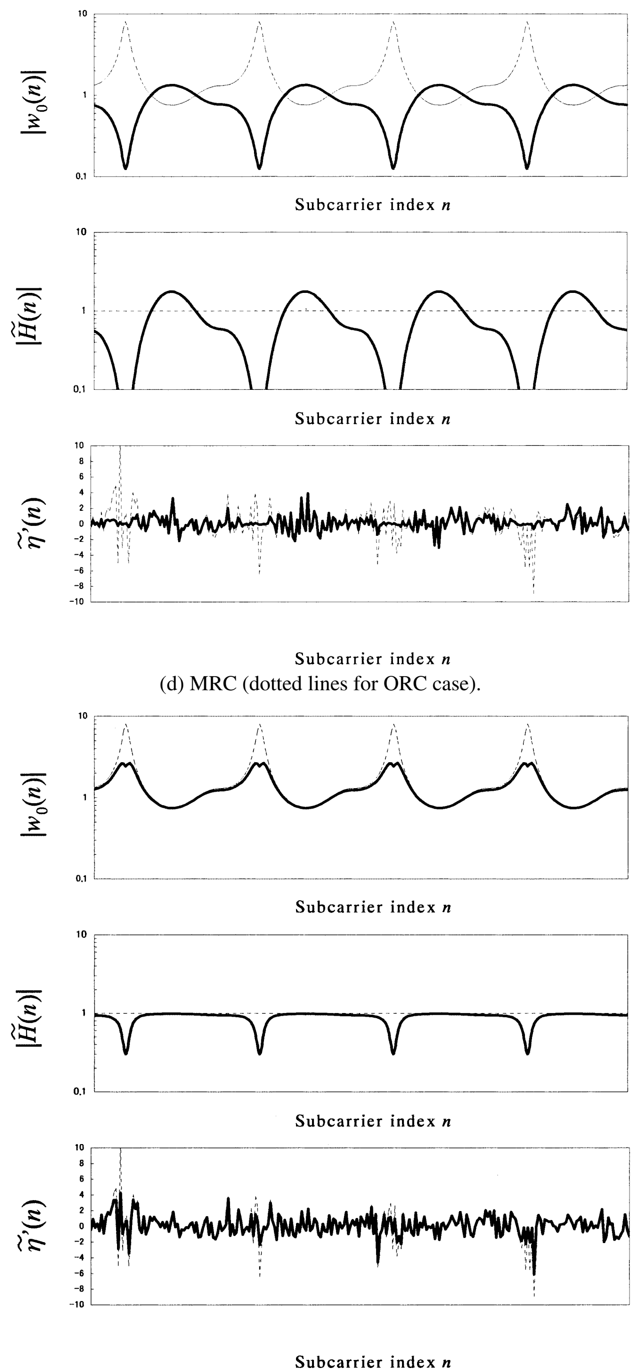
No antenna diversity (M=1) and an L=3-path channel having uniform power delay profile are assumed. Figures A· 1(b)–(e) illustrate the one shot observations of $|w_0(n)|$, $\left|\tilde{H}(n)\right|$ $(= |w_0(n)H_0(n)|)$ and $\tilde{\eta}'(n)$ $(= w_0(n)\tilde{\eta}_0(n))$ for ORC, EGC, MRC, and MMSEC for the given channel gain $H_0(n)$ of Fig. A· 1(a). The equalization weight of ORC is in inverse proportion to the channel gain and thus, a large noise enhancement is observed at the subcarrier where the channel gain $H_0(n)$ drops, while the frequency-nonselective channel is perfectly restored, i.e., $\left|\tilde{H}(n)\right| = 1$. In Figs. A· 1(c)–(e),



(a) Channel gain $H_0(n)$.

(b) ORC.

(c) EGC (dotted lines for ORC case).



(d) MRC (dotted lines for ORC case).

(e) MMSEC (dotted lines for ORC case).

Fig. A· 1 Equalization weight $|w_0(n)|$, channel gain $\left|\tilde{H}(n)\right|$ after equalization and noise $\tilde{\eta}'(n)$ after equalization for the given channel gain $H_0(n)$. No antenna diversity (M=1).

results of ORC are plotted as dotted curves for comparison. The EGC can avoid the noise enhancement since the magnitude of equalization weight is always unity, but the channel frequency-selectivity remains intact. The MRC can also suppress the noise enhancement as the EGC does, but in turn enhances the channel frequency-selectivity. On the other hand, the MMSEC suppresses the noise enhancement while weakening the frequency-selectivity. It is then plausible that the use of MMSEC provides a better BER performance in the multicode case.

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