PAPER

Chip Interleaved Multicode DS-CDMA with MMSEC in A Fading Channel

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SUMMARY Direct sequence code division multiple access (DS-CDMA) provides flexible data transmission in wide range of data rates by the use of orthogonal multicode multiplexing. In a multipath fading environment, the transmission performance of multicode DS-CDMA degrades as that of single code DS-CDMA does. Chip interleaving is known to improve the bit error rate (BER) performance of the single code transmission by altering the fading channel into severely time selective fading channel. However, this partially destroys orthogonality property among spreading codes and thus, significantly degrades the BER performance of multicode DS-CDMA. In this paper, we propose the joint use of chip interleaving and time-domain minimum mean square error combining (MMSEC) equalization to improve the multicode DS-CDMA transmission performance. It is confirmed by computer simulations that the joint use of chip interleaving and MMSEC equalization significantly improves the BER performance of multicode DS-CDMA and achieves better BER performance compared to the single code DS-CDMA using chip interleaving and maximal ratio combining (MRC).

key words: *multicode DS-CDMA, chip interleaving, MMSEC, fading channel*

1. Introduction

Recently, direct sequence code division multiple access (DS-CDMA), that provides flexible data transmissions in wide range of data rates by the use of orthogonal multicode multiplexing, is used in mobile communications systems [1], [2]. In mobile radio, multipath channel is created due to reflection and diffraction by obstacles between a transmitter and a receiver and the well-known multipath fading appears on the received signal. Multipath fading severely degrades the bit error rate (BER) performance. Rake receiver, antenna diversity reception, and channel coding are effective techniques to improve the BER performance, but rake receiver cannot be used in a frequency nonselective fading channel. Recently, chip interleaving that exploits the spreading process in DS-CDMA was proposed to improve the BER performance in the frequency nonselective fading channel [3].

In general, the channel impulse response stays almost constant over one data symbol period since the fading rate-to-data rate ratio is very small, e.g., for data transmissions of above several tens kbps. Such fading is called time nonselective fading. Orthogonal multicode DS-CDMA (hereafter simply referred to as multicode DS-CDMA) relies on this time nonselectivity of the channel, in which parallel data transmission is done using orthogonal spreading codes. Applying chip interleaving to multicode DS-CDMA so that chips belonging to one data symbol are spread in time, the equivalent fading channel seen at the receiver can be transformed into a severe time selective fading channel, where the channel gain varies over an interval of one symbol duration. Thus, variations in the received symbol energy after despreading can be made less; however, orthogonality property among parallel channels configured by orthogonal spreading codes is partially destroyed. As a consequence, the BER performance may degrade. In this paper, to reduce the influence of orthogonality destruction, we apply minimum mean square error combining (MMSEC) used for joint frequency-domain equalization and despreading in multicarrier CDMA (MC-CDMA) [4] to chip interleaved multicode DS-CDMA.

Objective of this paper is to show that the BER performance can be improved without relying on channel coding by transforming the fading channel seen at the receiver into a severe time selective fading channel. Of course, joint use of channel coding and chip interleaving can further improve the BER performance. However, this is not treated in this paper.

Remainder of this paper is organized as follows. Section 2 describes multicode DS-CDMA with chip interleaving and MMSEC equalization. The BER performance improvement in a Rayleigh fading channel is evaluated by computer simulations. The simulation results are presented in Sect. 3 to show that the multicode DS-CDMA with chip interleaving and MMSEC equalization provides superior BER performance to the single code DS-CDMA firstly in a frequency nonselective Rayleigh fading channel and secondly in a frequency selective Rayleigh fading channel, where rake combining can be employed.

2. Multicode DS-CDMA with Chip Interleaving and MMSEC Equalization

The transmission system model is illustrated in Fig. 1

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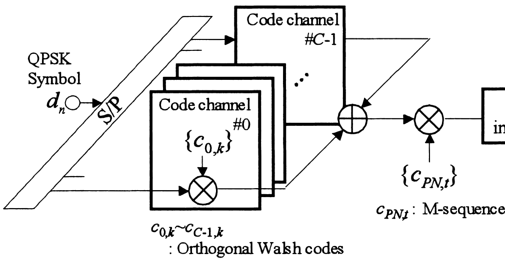
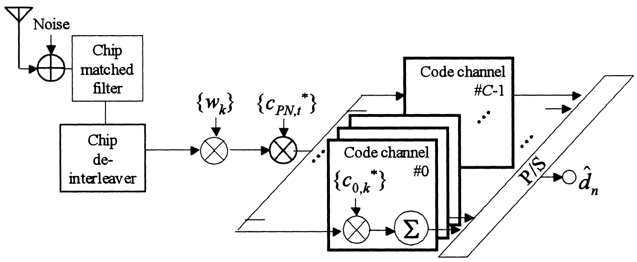


(a) Transmitter



(b) Receiver

Fig. 1 Multicode DS-CDMA transmission model.

for the case of frequency nonselective fading channel (L=1). For simplicity, it is assumed that L=1 (however, note that, in Sect. 3, the computer simulation is extended to the case of frequency selective fading channel having L independently Rayleigh faded paths (L=2∼4)).

2.1 Transmission System Model

At the transmitter, binary data sequence to be transmitted is transformed into the coherent quaternary phase shift keying (QPSK) symbol sequence $\{d_n = (\pm 1 \pm j)/\sqrt{2}; n = \cdots, -1, 0, 1, \cdots\}$, which is then serial-to-parallel (S/P) converted to form C parallel symbol sequences. The nth QPSK symbol is mapped to the (n mod C)th code channel. Chip-space discrete time representation is used hereafter. C parallel sequences are spread by orthogonal spreading codes $\{c_{i,k} = \pm 1; i = 0 \sim C-1, k = 0 \sim SF-1\}$, where SF represents the spreading factor. After summing (i.e., code multiplexing) the C parallel spread chip sequences, the long scramble sequence $\{c_{PN,t} = \pm 1; t = \cdots, -1, 0, 1, \cdots\}$ is multiplied in order to transform the multicode DS-CDMA signal into noise like signal. The resultant multicode DS-CDMA signal may be expressed using the equivalent baseband representation as

$$s_t = \sqrt{\frac{2S}{C}}\, c_{PN,t} \sum_{i=0}^{C-1} d_{i+C\lfloor t/SF \rfloor C_i, t \bmod SF}, \qquad (1)$$
$$\text{for} \quad t = \cdots, -1, 0, 1, \cdots$$

where S is the total transmit power and $\lfloor x \rfloor$ represents the largest integer smaller than or equal to x. Finally chip interleaving is applied before transmission of $\{s_t\}$ over a frequency nonselective fading channel.

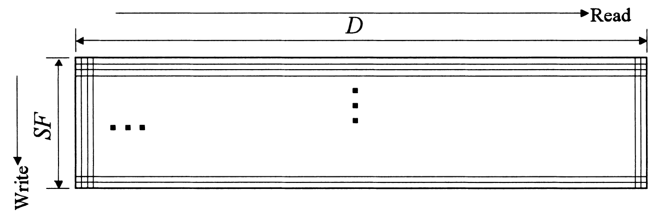


Fig. 2 Chip interleaver structure.

At the receiver, the received multicode signal is filtered with a matched filter, sampled at the chip rate, chip de-interleaved, and then one-tap time domain MMSEC equalization is applied to transform the time selective channel introduced by chip interleaving back to the nearly time nonselective channel. After multiplying the long scramble sequence, C copies of the resultant chip de-interleaved sequence are made, each being multiplied by one of the C orthogonal spreading codes to recover each of the C transmitted QPSK symbol sequences. This is called despreading. Finally, the recovered C QPSK symbol sequences are parallel-to-serial (P/S) converted into the single QPSK symbol sequence and then transformed into the binary transmitted data sequence.

2.2 Chip Interleaving

Chip interleaver in this paper uses an $SF \times D$-chip block interleaver as illustrated in Fig. 2 [3], where D represents the interleaving depth. The multicode chip sequence to be transmitted is grouped into blocks of D multicode DS-CDMA symbols (i.e., $C \times D$ QPSK symbols per block). The multicode chip sequence is written column by column and read out row by row. SF chips belonging to one multicode symbol are separated by D chips in time as illustrated in Fig. 3. At the receiver, the chip de-interleaver brings back the chip sequence into the original order. The use of chip interleaving increases the fading rate by D times, thereby transforming the channel into time selective fading channel; the equivalent propagation channel gain seen after chip de-interleaving varies over one QPSK symbol interval. As a result, time diversity effect is obtained and the received symbol energy varies less. However, multicode transmission relies on the condition that the channel gain remains constant over one QPSK symbol interval. Hence, using chip interleaving degrades the multicode transmission performance because of partial destruction of code orthogonality property. The time-domain MMSEC equalization can be applied to partially restore the code orthogonality.

As stated earlier, this paper is to show a possible way to improve the BER performance without using channel coding. In order to achieve this, chip interleaving and MMSEC equalization are applied. Chip interleaving requires much larger memory size compared

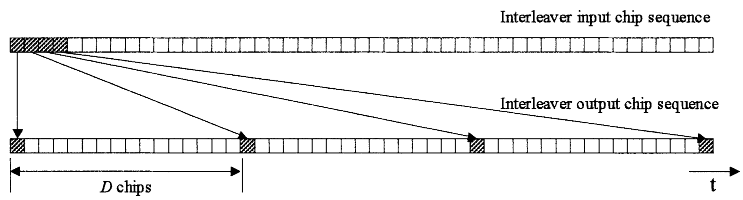


Fig. 3 Separation of SF chips belonging to one multicode symbol.

to bit interleaving used in a channel coded system and therefore, may be a difficult technique from the practical implementation view point. Hardware implementation issue is practically important, but we do not discuss this in the paper.

2.3 MMSEC Equalization

Well-known frequency-domain despreading techniques for MC-CDMA are orthogonal restoration combining (ORC) and MMSEC [4], [5]. They can be applied to our case. ORC can perfectly restore the orthogonality property of the received multicode DS-CDMA symbol and hence completely remove the inter-code interference; however, the noise enhancement is produced, thereby increasing the BER due to additive background noise. It is known that there exists a tradeoff between orthogonality restoration and noise enhancement. MMSEC equalization trades off orthogonality restoration with reducing noise enhancement and minimizes the BER [4]. MMSEC equalization provides superior BER performance to ORC.

Let the propagation channel gain and the received chip sample at the discrete time t be ξ_t and r_t, respectively; $\{\xi_t\}$ is the zero mean complex Gaussian process with unity variance. Without loss of generality, we consider the reception at the 0th signaling period, i.e., C QPSK symbols $\{d_i; i = 0 \sim C-1\}$ are received. SF received chips, each separated by D-chip time, belonging to the 0th multicode DS-CDMA symbol, are brought back to the original order by the chip de-interleaver. The equivalent baseband representation of the chip de-interleaved sample sequence $\{r_{kD}; k = 0 \sim SF-1\}$ for the 0th signaling period may be expressed as

$$\begin{aligned} r_{kD} &= \xi_{kD} s_{kD} + n_{kD} \\ &= \sqrt{\frac{2S}{C}} \xi_{kD} \sum_{i=0}^{C-1} d_i c_{i,k} + n_{kD} \end{aligned} \tag{2}$$

for $k = 0 \sim SF-1$, where $\{n_{kD}; i = 0 \sim C-1\}$ is complex Gaussian noise sample sequence with zero mean and variance $2N_0/T$ (N_0 is the single-sided power spectrum density of the additive white Gaussian noise (AWGN) and T is the multicode DS-CDMA symbol length). The samples $\{r_{kD}; k = 0 \sim SF-1\}$ are multiplied by the MMSEC equalization weights $\{w_k; k = 0 \sim SF-1\}$ and orthogonal spreading code $\{c_{i,k}; k = 0 \sim SF-1\}$ to be summed up (this is called despreading) for obtaining the decision variable $\hat{d}_i$ for the ith transmitted QPSK symbol, $i = 0 \sim C-1$. Assuming ideal channel estimation, MMSEC equalization weight $w_{\mathrm{MMSEC},k}$ for QPSK is given by [4]

$$w_{\mathrm{MMSEC},k} = \frac{\xi_{kD}^*}{|\xi_{kD}|^2 + \left[2\frac{C}{SF}\left(\frac{E_b}{N_0}\right)\right]^{-1}}, \tag{3}$$

where E_b/N_0 represents the average received signal energy per bit-to-AWGN power spectrum density ratio and $(.)^*$ denotes complex conjugate. Hence, $\hat{d}_i$ is given by

$$\hat{d}_i = \sum_{k=0}^{SF-1} r_{kD} \cdot w_{\mathrm{MMSEC},k} \cdot c_{i,k} \tag{4}$$

for $i = 0 \sim SF-1$. C decision variables $\{\hat{d}_i; i = 0 \sim C-1\}$ are parallel-to-serial converted and then, QPSK demodulated to recover the transmitted binary sequence.

Complexity for computing the MMSEC equalization weights is similar to the MC-CDMA case. Weight updating rate is dependent on the fading rate, i.e., the fading maximum Doppler frequency f_D and therefore, is the same for chip interleaved DS-CDMA and MC-CDMA if the carrier frequency is the same.

3. Computer Simulation

3.1 Simulation Condition

Table 1 summarizes the simulation condition. L-path frequency selective Rayleigh fading channel (L=1∼4) with the maximum Doppler frequency normalized by the chip rate of $f_D T_c$=0.000025 is assumed (corresponding to a traveling speed of 54 km/h for the carrier frequency of 2 GHz and the chip rate of $1/T_c$=3.84 M chip/s).

In order to clearly show how the joint use of chip interleaving and MMSEC equalization improves the BER performance of multicode DS-CDMA, the frequency nonselective channel (i.e., L=1), where the rake combining effect cannot be expected, is considered as a special case in Sects. 3.2–3.4. Then, the evaluation is extended to the case of frequency selective fading channel in Sect. 3.5.

Table 1 Simulation condition.

Modulation		Coherent QPSK
Spreading factor		SF=16 and 64
Code multiplexing	Spreading codes	Orthogonal Walsh codes
	Multiplexing order	C=1~16
Scrambling code		M-sequence with 4095-chip repetition period
Interleaving depth		D=512~16384
Channel model	Fading type	L-path frequency selective Rayleigh fading
	$f_D T_c$	0.000025
Channel estimation		Ideal

Table 2 Interleave depth and fading correlation.

D	$f_D T_c \times D$	Fading correlation
512	0.0128	0.9984
1024	0.0256	0.9936
2048	0.0512	0.9743
4096	0.1024	0.8992
8192	0.2048	0.6270
16384	0.4096	-0.0843

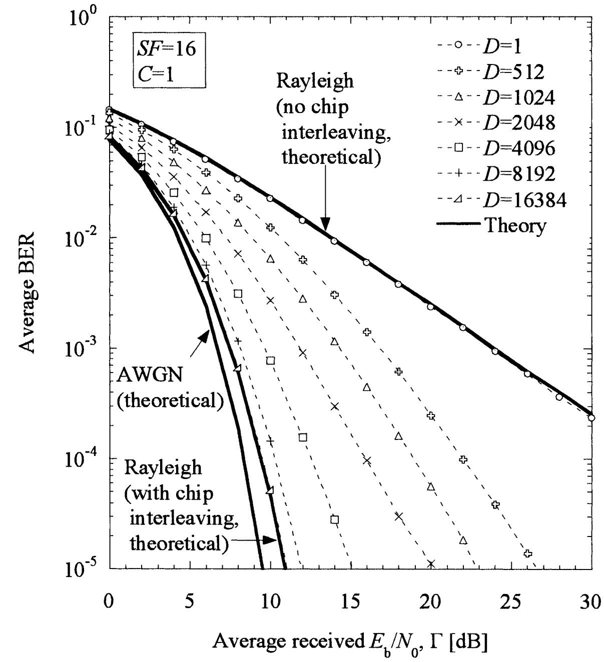


Fig. 4 Average BER performance for the single code case.

3.2 Single Code Case ($C = 1$)

MMSEC equalization is not required for the single code transmission and maximal ratio combining (MRC) is used. Assuming ideal channel estimation, MRC weight $w_{\mathrm{MRC},k}$ is given by

$$w_{\mathrm{MRC},k} = \xi^*_{kD}. \tag{5}$$

The performance improvement achievable by the chip interleaving and MRC is evaluated. Since the SF chips belonging to one QPSK symbol are transmitted with the separation of D chips in time, D times faster fading is seen after chip de-interleaving. Table 2 shows the measured fading correlation ρ between two consecutive chips for different values of D. The well-known Jakes model [6] is assumed for multipath fading, in which all multipath waves having the same time delay arrives at the receiver from all directions with the same power. The fading auto-correlation function is given by $J_0\ (2\pi f_D \tau)$, where $J_0(.)$ is the 0th order Bessel function and τ represents the time difference. Hence, ρ can be computed using $\rho = J_0\ (2\pi f_D T_c \times D)$. As the value of D increases, the fading correlation becomes smaller and the propagation channel gain varies even during the time interval of one multicode DS-CDMA symbol. It can be seen from Table 2 that D=16384 gives almost independent fading and thus, the time diversity effect achieved by chip interleaving is almost saturated.

Figure 4 plots the simulated average BER performance of the single code transmission case (C=1) with D as a parameter. As is expected, the BER performance improves as the value of D increases. When no chip interleaving is applied (i.e., D=1), the BER reduces in proportion to the inverse of the average received E_b/N_0, Γ, and a BER=10^{-4} is achieved at the average received E_b/N_0=34.0 dB. The required E_b/N_0 for BER=10^{-4} can be reduced by 12.0 dB by increasing D from 1 to 512. The additional reduction in the required E_b/N_0 is 3.0(6.0) dB when the value of D increases from 512 to 1024(2048). The BER performance continuously improves by the use of larger D and approaches that of no fading case. The required E_b/N_0 for BER=10^{-4} becomes close to the no fading case by about 4.1(1.9) dB when D=4096(8192). The BER performance when D=8192 and 16384 are almost the same.

Assuming that the fading channel gains $\{\xi_{kD}\}$ are independent of each other, the theoretical BER can be derived. The decision variable for the ith QPSK symbol is given by Eq. (4) with $w_{\mathrm{MMSEC},k}$ being replaced by $w_{\mathrm{MRC},k}$. Signal-to-noise ratio (SNR) per QPSK symbol is given by

$$SNR = 2 \cdot \left(\frac{\Gamma}{SF}\right) \sum_{i=0}^{SF-1} |\xi_{kD}|^2 = 2\gamma, \tag{6}$$

where Γ and γ are the average received E_b/N_0 and instantaneous received E_b/N_0, respectively. Since the real and imaginary parts of ξ_{kD} are independent and identically distributed (i.i.d.) complex Gaussian variables, γ is χ-square distributed with $2SF$ degrees of freedom. The probability density function of γ can be obtained as follows [7]:

$$p(\gamma) = \frac{\left(\frac{\gamma}{\Gamma/SF}\right)^{SF-1}}{(SF-1)!(\Gamma/SF)} \exp\left(-\frac{\gamma}{\Gamma/SF}\right), \qquad (7)$$

which is equivalent to SF-branch MRC diversity reception with uncorrelated fading with the average received E_b/N_0 per branch of Γ/SF. The fading nature experienced after despreading tends to disappear as a result of chip interleaving. The average BER can be calculated from [7]

$$\begin{aligned} P_b &= \int_0^\infty \frac{1}{2}\mathrm{erfc}(\sqrt{\gamma})p(\gamma)d\gamma \\ &= \left[\frac{1-\mu}{2}\right]^{SF} \sum_{k=0}^{SF-1} \binom{SF-1+k}{k} \left[\frac{1+\mu}{2}\right]^k \\ &\approx \left(\frac{SF}{4\Gamma}\right)^{SF} \quad \text{for } \Gamma \gg 1, \end{aligned} \qquad (8)$$

where

$$\mu = \sqrt{\frac{\Gamma}{\Gamma + SF}}. \qquad (9)$$

On the other hand, the average BER without chip interleaving is obtained by letting SF=1 in Eq. (8) and is given by

$$\begin{aligned} P_b &= \frac{1}{2}\left[1 - \sqrt{\frac{\Gamma}{\Gamma+1}}\right] \\ &\approx \frac{1}{4\Gamma}, \text{ for } \Gamma \gg 1. \end{aligned} \qquad (10)$$

Comparison of Eqs. (8) and (10) implies that the average BER performance improves as the spreading factor increases. For comparison, the theoretical BER performances with and without chip interleaving, computed from Eqs. (8) and (10), respectively, are plotted for SF=16 in Fig. 4. Also plotted is the BER performance in the AWGN channel, which is given by $P_b = \frac{1}{2}\mathrm{erfc}\sqrt{\gamma}$. The simulated BER performances in the fading channel with and without chip interleaving (i.e., D=16384 and 1) show a good agreement with the theory.

3.3 Multicode Case ($C > 1$)

It is seen from Fig. 4 that as the value of D increases, the BER performance improves and approaches that of the AWGN channel. In the following, assuming D=4096 as a typical case, we discuss how the BER performance is affected by the code multiplexing order C (however, note that the impact of D is also evaluated for C=16 in Fig. 7). Figure 5 plots the simulated average BER performance of multicode DS-CDMA using chip interleaving and MRC with C as a parameter when SF=16 and D=4096. When C=1 and 2, the use of chip interleaving significantly improves the average BER performance compared to the no chip interleaving case. However, as the value of C increases above 2, the average BER performance degrades significantly and produces the BER floor due to inter-code interference. The BER floor can be completely eliminated when MRC is replaced by MMSEC equalization. This is shown in Fig. 6, which plots the simulated average BER performance of multicode DS-CDMA using chip interleaving and MMSEC equalization with C as a pa-

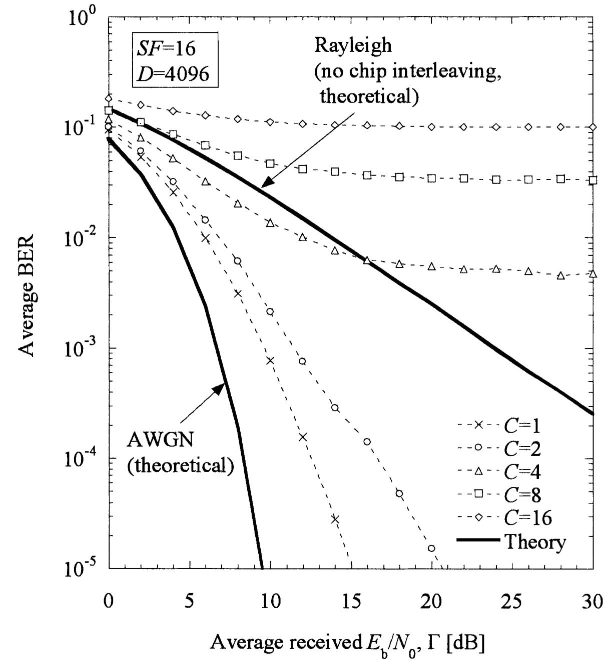


Fig. 5 Average BER performance of multicode DS-CDMA using chip interleaving and MRC.

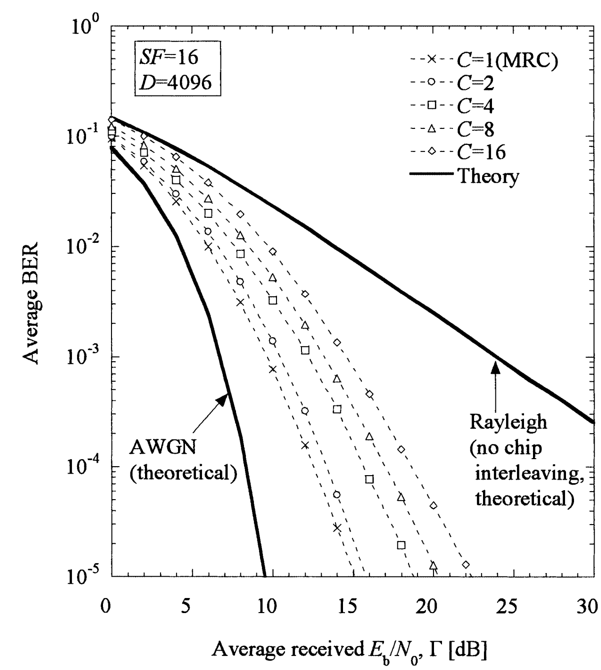


Fig. 6 Average BER performance of multicode DS-CDMA using chip interleaving and MMSEC equalization.

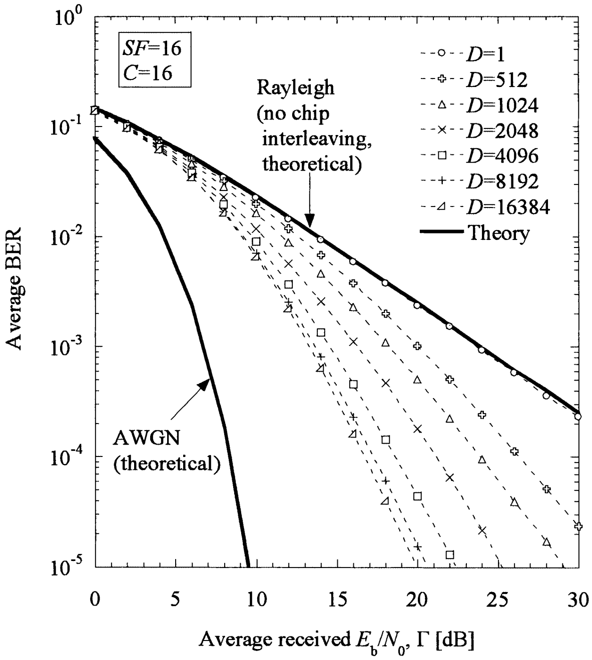


Fig. 7 Impact of interleaving depth D for $SF = C = 16$.

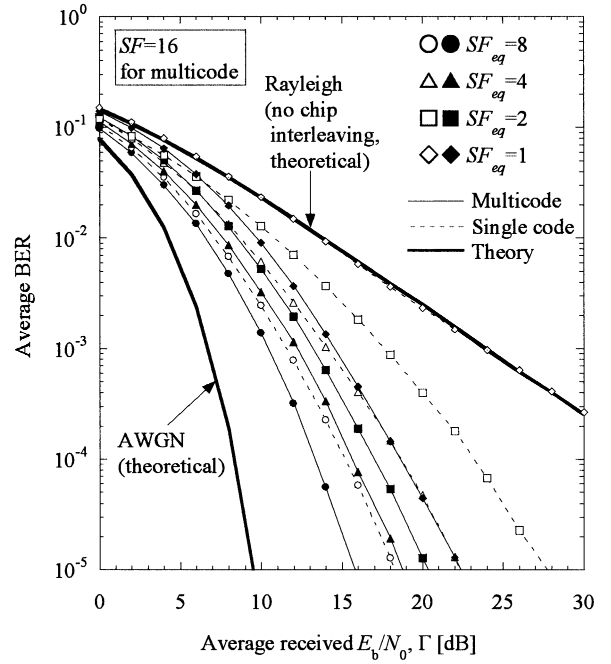


Fig. 8 Performance comparison of multicode DS-CDMA using chip interleaving and MMSEC equalization and single code DS-CDMA using chip interleaving and MRC.

rameter when SF=16 and D=4096. It can be seen that the use of chip interleaving always provides better BER performance than the no chip interleaving case even though the BER performance with chip interleaving degrades as the value of C increases. Even when C=16, the required E_b/N_0 for BER=10^{-4} can be reduced by 15.4 dB with chip interleaving.

It is understood from Fig. 4 that for the single code case (C=1), as the value of D increases, the larger time diversity effect can be obtained, thereby improving the BER performance. In the multicode case, however, larger inter-code interference is produced. How the selection of D impacts the achievable BER performance with MMSEC equalization is illustrated in Fig. 7 for C=16 (producing the largest inter-code interference when SF=16). It can be clearly seen from Fig. 7 that as the value of D increases, the BER performance with MMSEC equalization consistently improves (but the improvement almost saturates for $D > 8192$). This is because the MMSEC equalization can equalize the chip-interleaved channel (time selective channel) into the nearly time nonselective channel while reducing the noise enhancement.

3.4 Performance Comparison of Single Code Transmission and Multicode Transmission

So far, it has been confirmed that the use of chip interleaving can significantly improve the BER performance of multicode DS-CDMA. For the same chip rate, single code DS-CDMA with reduced spreading factor can be used instead of multicode DS-CDMA. Hence, it is interesting to compare the achievable BER performances of multicode DS-CDMA and single code DS-CDMA for the same data rate and chip rate. For this purpose, the equivalent spreading factor $SF_{eq} = SF/C$ is introduced. Note that for the single code case, the equivalent spreading factor is the same as the spreading factor SF itself.

Figure 8 shows the performance comparison of multicode DS-CDMA using chip interleaving and MMSEC equalization and single code DS-CDMA using chip interleaving and MRC. For all values of SF_{eq}, multicode DS-CDMA provides better BER performance. The reason for this is due to the larger number of time diversity branches for multicode DS-CDMA when the equivalent spreading factor is the same. The number N of time diversity branches is $N = C \times SF_{eq}$ for multicode DS-CDMA, while that of the single code DS-CDMA is N=SF_{eq}. This larger number of time diversity branches offsets the degradation due to inter-code interference produced by time selective fading. For the case of SF_{eq}=1 (i.e., C=16), the reduction in the required E_b/N_0 for BER=10^{-4} is 15.4 dB as shown earlier. As the value of SF_{eq} increases the amount in the reduction of required E_b/N_0 decreases, but as much as 1.9 dB reduction can still be achieved when SF_{eq}=8.

3.5 Performance Improvement in a Frequency Selective Fading Channel

So far, we have evaluated the effect of chip interleaving and MMSEC equalization in a frequency nonselective fading channel. It is interesting to see how the use of chip interleaving and MMSEC equalization can further improve the performance in a frequency selective fading channel, where rake combining can be employed to improve the BER performance. The receiver structure of Fig. 1(b) must be modified. We assume L-path Rayleigh fading having uniform power delay profile. Let the path gains of L propagation paths at the discrete time t be $\xi_{l,t}$ and their time delays be τ_l, $l = 0 \sim L-1$, where $\{\xi_{l,t};\ l = 0 \sim L-1\}$ are i.i.d. complex Gaussian processes with zero-mean and variance of $1/L$. In the case of L-path frequency selective channel, L copies of the chip-matched filter output sequence are made and time aligned according to the time delays $\{\tau_l\}$ of L propagation paths. Each time aligned chip sequence is input to the respective chip de-interleaver. Then, one-tap time-domain MMSEC equalization (MMSEC equalization weights for frequency selective channel is given later) is applied to each chip de-interleaved sequence and coherently summed up (this is called rake combining) to produce the time-domain MMSEC equalized and rake combined output chip-sequence. This is illustrated in Fig. 9. The remaining process from the chip de-interleaver onward is identical to the L=1 case illustrated in Fig. 1(b).

In the presence of L propagation paths, the time-domain MMSEC equalized and rake combined output for the 0th signaling period is represented as

$$\hat{d}_i = \sum_{k=0}^{SF-1}\left(\sum_{l=0}^{L-1} r_{kD+\tau_l}\cdot w_{\mathrm{MMSEC},l,k}\right)c_{i,k}, \qquad (11)$$

where $w_{\mathrm{MMSEC},l,k}$ represents the MMSEC equalization weight associated with the lth propagation path. When rake combining is used, since L different paths can be viewed as independently faded antenna diversity branches but with reduced average power by a factor of L, we apply the MMSEC equalization weights derived in [8]. $w_{\mathrm{MMSEC},l,k}$ is given by

$$w_{\mathrm{MMSEC},l,k} = \frac{\xi^*_{l,kD}}{\sum_{l=0}^{L-1}|\xi_{l,kD}|^2 + \left[2\frac{C}{SF}\left(\frac{E_b}{N_0}\right)\right]^{-1}}, \qquad (12)$$

where $\xi_{l,t+\tau_l} = \xi_{l,t}$ is assumed since very slow fading is

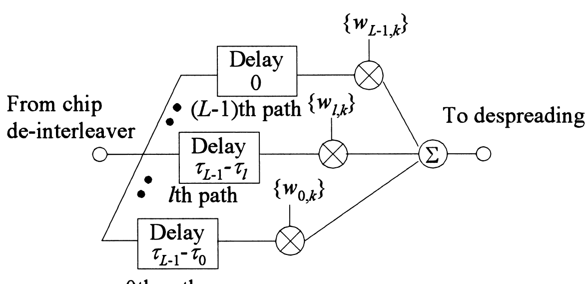
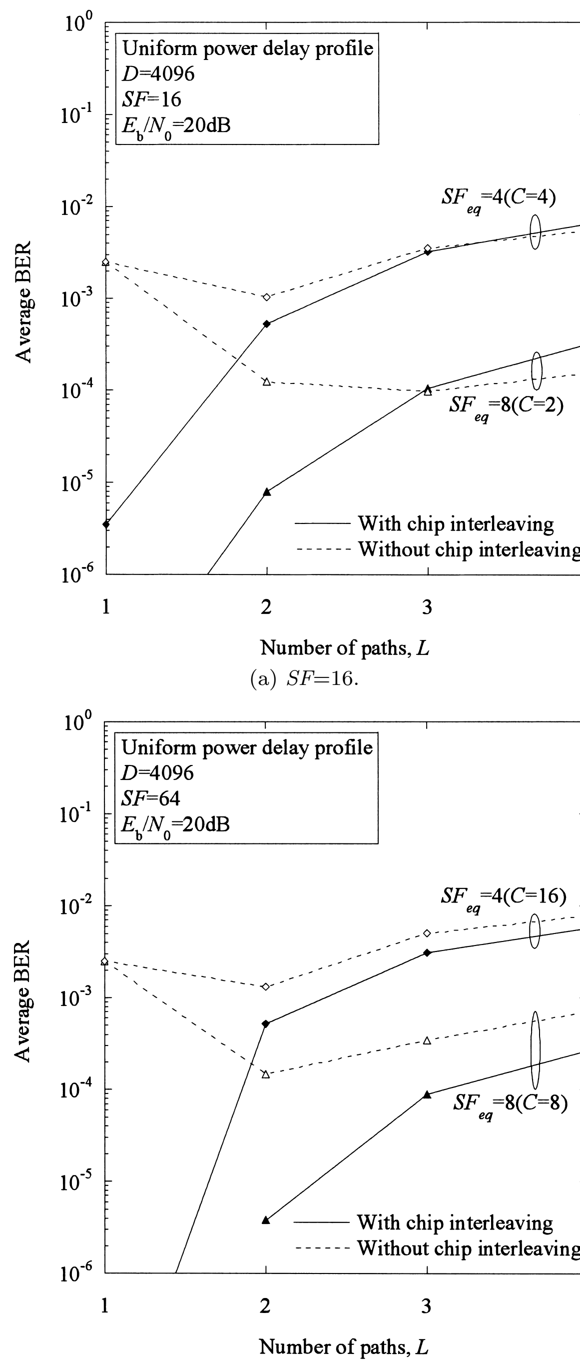


Fig. 9 MMSEC equalization and rake combining.

assumed, i.e., $f_D T_c$=0.000025.

In a frequency selective channel, inter-code interference increases due to asynchronism among different propagation paths in addition to chip interleaving while path diversity effect owing to rake combining can be expected for no chip interleaving case. It is interesting to see how the BER performance achievable by the use of chip-interleaving and MMSEC equalization is impacted by frequency selective fading. Figure 10 plots the av-



(a) SF=16.

(b) SF=64.

Fig. 10 Impact of number L of propagation paths.

erage BER as a function of the number L of propagation paths for the average received E_b/N_0=20 dB. Uniform power delay profile of the propagation channel and D=4096 are assumed. It is seen from Fig. 10 that as the value of L increases, the average BER with chip interleaving and MMSEC equalization increases due to increased inter-code interference. However, without chip interleaving, the average BER reduces first due to path diversity effect as the value of L increases from 1 to 2, but in turn increases for $L > 2$ due to increased inter-code interference as in the chip interleaving case. Comparison shows that when SF=64, the introduction of chip-interleaving yields the BER performance superior to the no chip interleaving case even in a frequency selective fading channel although the performance superiority becomes less as L increases. However, when SF=16, the BER performance of SF_{eq}=8 (C=2) with chip interleaving is slightly inferior to that with no chip interleaving when L=4 (note that the BER inferiority becomes less for smaller SF_{eq}, i.e., SF_{eq}=4 (C=4)). This may be due to non-uniform distribution of inter-code interference among different spreading codes for the case of small spreading factors, but detailed discussion on this is left for a future study.

4. Conclusion

In this paper, the joint use of chip interleaving and MMSEC equalization was proposed to significantly improve the multicode DS-CDMA transmission performance in a fading channel. The average BER performance achievable by the use of chip interleaving and MMSEC equalization was evaluated by computer simulation. Following are the summary of the simulation results:

(a) The use of chip interleaving alters the fading channel to severely time selective fading channel so that the channel gain varies rapidly even during a symbol interval. Since this provides time diversity effect, the BER performance of single code DS-CDMA can be significantly improved.
(b) In the case of multicode DS-CDMA, chip interleaving produces intercode interference, thereby degrading the transmission performance. Intercode interference is eliminated by applying MMSEC equalization. The resultant BER performance is better than the single code DS-CDMA for the same equivalent spreading factor.
(c) The BER performance of chip interleaved multicode DS-CDMA is superior to the no chip interleaving case even in a frequency selective fading channel (if small spreading factor, e.g., SF=16, is not used) although the performance superiority becomes less as L increases.

In this paper, ideal channel estimation was assumed for computing the MMSEC equalization weights. Pilot-assisted channel estimation can be applied to the chip interleaved system as proposed in [3]. For both cases with and without chip interleaving, the BER performance may degrade due to channel estimation error. How the pilot-assisted channel estimation degrades the BER performance of multicode DS-CDMA with chip interleaving and MMSEC equalization is left as a practically important future study. Introduction of channel coding (e.g., turbo coding) in addition to chip interleaving may be able to further improve the BER performance of multicode DS-CDMA. This has been shown for the case of single-code DS-CDMA (in this case, MMSEC equalization is not necessary) [3]. How the additional use of channel coding further improves the BER performance of multicode DS-CDMA is left as a future study. Also an interesting study is reducing the peak-to-average power ratio (PAR) problem arising in multicode DS-CDMA, but note that this PAR problem is present in any multicarrier systems, e.g., MC-CDMA and orthogonal frequency division multiplexing (OFDM), which have been gaining a lot of attention for broadband mobile wireless access [9].

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