PAPER *Special Section on Spread Spectrum Techniques and Applications*

Multi-Carrier DS-CDMA Using Frequency Spread Coding

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SUMMARY In this paper, a type of multi-carrier direct sequence code division multiple access (MC-DS-CDMA) system which uses frequency spread coding is proposed and investigated for the down-link. An MC-DS-CDMA system is a combined system of CDMA and multi-carrier modulation. This system is often categorized as a "serial to parallel (S/P) type" system because serial to parallel converted data symbols are transmitted. They use different sub-carriers which are narrow-band DS waveforms. In this system, benefits of path or frequency diversity can not be obtained because of the narrow-band transmission of each data symbol. In order to benefit from the diversity, we propose to adopt frequency spread coding in an MC-DS-CDMA system. The proposed system exploits frequency diversity without additional redundancy, i.e., no frequency or time redundancy is required to improve the performance. Computer simulation is carried out in a frequency selective fading channel and the results show its effectiveness in terms of average bit error rate (BER). Furthermore, the proposed system is compared with a multi-carrier (MC-) CDMA system which is often categorized as a "copy type" system and a single-carrier (SC-) DS-CDMA system using a RAKE receiver.

key words: *frequency selective fading, multi-carrier DS-CDMA, frequency spread coding, frequency diversity*

1. Introduction

In the field of mobile radio communications, it is desirable to support high data rate applications such as image and video. However, the ability to achieve high bit rates at low error rates over wireless channels is severely restricted by the frequency selectivity of channels caused by multiple propagation paths with different time delays [1].

A code division multiple access (CDMA) system using direct sequence spread spectrum (DS-SS), referred to as a DS-CDMA system, could be a potential candidate for next generation mobile radio communications systems [2]. This is because it is known to have resistance to the frequency selectivity of channels. In a DS-CDMA system, its capacity is limited by self-interference (SI) and multiple access interference (MAI), which result from the imperfection of auto-correlation and cross-correlation characteristics of spreading codes, respectively. Although in the synchronized down-link (from base to mobile direction) one can use zero cross-correlated orthogonal codes resulting in no MAI in flat fading channels, the orthogonality will be no longer guaranteed in frequency selective fading channels because of inter-chip interference (ICI). The ICI will cause not only MAI but also SI, and they degrade the system performance.

As an interesting approach to combat the effect of ICI in frequency selective fading channels, a number of communications systems based on a combination of CDMA and multi-carrier modulation have been recently proposed [3]–[11]. With a multi-carrier modulation technique, the entire bandwidth is subdivided into several narrow-band sub-channels operating at lower data rates. Thus only flat fading, which has no ICI, is experienced in each sub-channel if the number of sub-carriers is chosen appropriately. Moreover, orthogonal frequency division multiplexing (OFDM) [12]–[14], which is one particular format of multi-carrier modulation, can achieve high spectral efficiency because the spectrum of successive sub-carriers is allowed to overlap.

The combined CDMA systems with OFDM are mainly categorized into two types. One is a "copy type" system and the other is a "serial to parallel (S/P) type" system.

In the former system, multiple copies of the same data symbol, each multiplied by one chip of a user specific spreading code, are transmitted on different sub-carriers. In a sense the spreading operation is performed in frequency domain. This system is referred to as a multi-carrier (MC-)CDMA system [4]–[7]. Since replicas of the same data symbol are transmitted on different sub-carriers, frequency diversity can be exploited even without error-correction coding. However, MAI still occurs even in the synchronized down-link.

In the latter system, which is the S/P type and of interest in this paper, serial to parallel converted data symbols are DS-SS modulated respectively using a user specific spreading code, and those DS signals are transmitted in parallel on different sub-carriers. This system is referred to as a multi-carrier (MC-)DS-CDMA system [8]–[11]. In this system, it is guaranteed that there is no MAI in the synchronized down-link in a cell in slow frequency selective fading channels. However, benefits of path diversity which is inherent in wide-band transmission systems can not be obtained because each data symbol is assigned to one of the narrow-band

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sub-channels and only one path is resolvable in each sub-channel. Although frequency diversity is exploited by applying an error-correction code across the sub-carriers [9]–[11], transmission of redundant data, i.e., reduction of bandwidth efficiency, is involved.

As an alternative for exploiting frequency diversity, frequency spread coding has been proposed [15], [16]. Although the constellation size is increased, bandwidth expansion is not necessary because no redundancy is required of the method.

In this paper, it is proposed to adopt frequency spread coding in an MC-DS-CDMA (S/P type) system in order to benefit from frequency diversity in frequency selective fading channels without reducing bandwidth efficiency. The proposed system is investigated for the down-link of a single cell environment in a slow frequency selective fading channel. The average bit error rate (BER) performance of the proposed system is given by computer simulation, and it is compared with that of an MC-DS-CDMA system without frequency spread coding, denoted as the "conventional system." Furthermore, the proposed system is compared with an MC-CDMA (copy type) system and a single-carrier (SC-)DS-CDMA system using a RAKE receiver.

This paper is organized as follows. In Sect. 2, the channel and system models are presented. Computer simulation results are shown in Sect. 3. Finally, Sect. 4 concludes this paper.

2. System Model

2.1 Channel Model

We consider a frequency selective fading channel modeled as a tapped delay line. Therefore, the complex lowpass equivalent impulse response is given by [1]

$$h(\tau;t) = \sum_{\zeta=1}^{N_p} h_\zeta(t)\delta(\tau-\tau_\zeta), \tag{1}$$

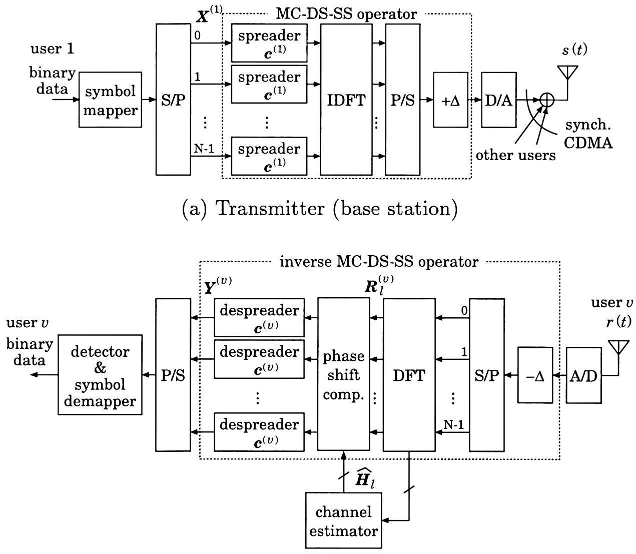
where $\delta(t)$ represents the Dirac delta function, τ_ζ is the propagation delay for the ζ-th path, $h_\zeta(t)$ is the complex envelope of the signal received on the ζ-th path, which is an independent zero mean complex Gaussian process, and N_p is the number of paths.

2.2 Multi-Carrier DS-CDMA System

In this subsection, a transmission system of an MC-DS-CDMA system [8] is considered for the down-link.

2.2.1 Transmitter Model

The block diagram of a transmitter (base station) of an MC-DS-CDMA system is shown in Fig.1 (a). Quadrature phase shift keying (QPSK) is utilized for symbol-mapping. In the transmitter, symbol-mapped consecutive data stream where each symbol has duration



(a) Transmitter (base station)

(b) Receiver (mobile station)

Fig. 1 MC-DS-CDMA system.

T_d is serial to parallel converted into N sub-channels. The new data symbol duration in each sub-channel is $T_s = NT_d$. Each sub-stream is spread by a user specific spreading code and transmitted with one of the N sub-carriers which is a narrow-band DS waveform. Synchronous transmission is achieved in the down-link, so that the equivalent lowpass transmitted signal can be written as

$$s(t) = \sum_{i=-\infty}^{+\infty}\sum_{u=1}^{K} s_i^{(u)}(t-iT_s), \tag{2}$$

where K is the number of users supplied at the base station and $s_i^{(u)}(t)$ represents the i-th MC-DS-SS symbol waveform of user u which is given by

$$\begin{aligned} s_i^{(u)}(t) \;=\; &\sum_{k=0}^{N-1}\sum_{l=0}^{L-1} X_{k,i}^{(u)} c_l^{(u)} e^{j2\pi f_k(t-lT_c)} \\ &\cdot p_{T_c}(t-lT_c), \quad -\Delta \le t \le -\Delta + T_s, \end{aligned} \tag{3}$$

where L is the length of a user specific spreading code and $c_l^{(u)} \in \{-1,+1\}$ is the l-th chip of the spreading code of user u which is represented by $\boldsymbol{c}^{(u)} = \left(c_0^{(u)}, c_1^{(u)}, \ldots, c_{L-1}^{(u)}\right)$. The spreading code is used in all sub-channels in common. Also for explaining notations in Eq. (3), f_k is the frequency of sub-carrier k which is represented by

$$f_k = f_0 + \frac{k}{t_c}, \tag{4}$$

where f_0 is the lowest frequency of sub-carriers, and $p_{T_c}(t)$ is a pulse waveform of each chip defined as

$$p_{T_c}(t) = \begin{cases} 1, & -\Delta \le t \le t_c, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

where Δ is the guard interval, t_c is the observation period and $T_c = \Delta + t_c$ is the MC-DS-SS chip duration. Note that the MC-DS-SS symbol duration is corresponding to T_s. The relation between the MC-DS-SS symbol duration and the MC-DS-SS chip duration is $T_s = LT_c$, i.e., an MC-DS-SS symbol consists of L MC-DS-SS chips. Each MC-DS-SS chip is yielded by an OFDM operation comprising an inverse discrete Fourier transform (IDFT), a parallel to serial conversion, and a cyclic prefix extension for the guard interval. The combination of spreading and the OFDM operation is referred to as an MC-DS-SS operation. Note that the addition of a guard interval Δ implies an increase in the actual chip rate $1/t_c$ by a factor of $(\Delta + t_c)/t_c$ if the symbol rate at the input of the MC-DS-SS operator, $1/T_s$, is kept constant.

Also in Eq. (3), $X_{k,i}^{(u)}$ is the k-th component of the i-th input sequence of user u at the MC-DS-SS operator. We use a vector $\boldsymbol{X}_i^{(u)}$ to denote the i-th input sequence of user u, i.e.,

$$\boldsymbol{X}_i^{(u)} = \left(X_{0,i}^{(u)}, X_{1,i}^{(u)}, \ldots, X_{N-1,i}^{(u)}\right). \tag{6}$$

In the conventional MC-DS-CDMA system, the input sequence is a data-symbol sequence. On the other hand, the input sequence in the proposed system is not a data-symbol sequence. The input sequence in the proposed system is described in Sect. 2.4.1.

2.2.2 Receiver Model

The block diagram of a receiver of the MC-DS-CDMA system for mobile station v is presented in Fig.1 (b). Through a wireless channel, the transmitted signal $s(t)$ is disturbed by multipath fading and additive white Gaussian noise (AWGN). The received signal is expressed as

$$r(t) = \int_0^{\infty} s(t-\tau)h(\tau;t)d\tau + n(t), \tag{7}$$

where $n(t)$ is a complex Gaussian noise with double sided power spectral density $N_0/2$, and $h(\tau;t)$ is the complex lowpass equivalent impulse response of a channel represented by Eq. (1). On the received signal $r(t)$, an inverse OFDM operation is performed at every MC-DS-SS chip. The inverse OFDM operation comprises guard interval removing, a serial to parallel conversion, and a discrete Fourier transform (DFT). The output of the k-th sub-carrier branch at time $iT_s + lT_c$ is expressed as

$$R_{k,l,i} = \frac{1}{t_c}\int_{iT_s+lT_c}^{t_c+iT_s+lT_c} r(t)e^{-j2\pi f_k(t-iT_s-lT_c)}dt. \tag{8}$$

Let τ_{max} be a maximum delay spread and f_D be a maximum Doppler frequency. On the assumption that $\Delta > \tau_{max}$ and $T_c \ll 1/f_D$, i.e., no ICI exists and the channel parameters are constant over several consecutive MC-DS-SS chip intervals, each sub-channel acts like a slow flat fading channel. Therefore, $R_{k,l,i}$ is expressed as

$$R_{k,l,i} = H_{k,l,i}\sum_{u=1}^{K} X_{k,i}^{(u)} c_l^{(u)} + \eta_{k,l,i}, \tag{9}$$

where $\eta_{k,l,i}$ is a zero mean Gaussian random variable with variance $N_0/2$, and $H_{k,l,i}$ describes the channel response at a sub-carrier frequency f_k, given as

$$H_{k,l,i} = \sum_{\zeta=1}^{N_p} h_\zeta(iT_s + lT_c)e^{-j2\pi f_k \tau_\zeta}. \tag{10}$$

After compensating the phase shift, despreading is performed on the signals in each sub-carrier branch. A despread data symbol of user v on the k-th branch can be written as

$$Y_{k,i}^{(v)} = \sum_{l=0}^{L-1} \frac{\widehat{H}_{k,l,i}^{*}}{|\widehat{H}_{k,l,i}|} R_{k,l,i}\, c_l^{(v)}, \tag{11}$$

where $\widehat{H}_{k,l,i}$ is an estimate of the channel response, and $(\cdot)^*$ denotes complex conjugation. Although consideration of channel estimation is necessary in order to provide the estimate, it is omitted and perfect channel estimation is assumed. The operation comprising the inverse OFDM operation, phase shift compensation, and despreading, is referred to as an inverse MC-DS-SS operation. The despread signals yielded by the inverse MC-DS-SS operation are parallel to serial converted, then data detection and symbol-demapping are held.

As mentioned before, the system is robust against the frequency selectivity of channels. However, the received signal quality of data symbols is different at respective sub-channels as shown in Fig.2. If a sub-channel is located in a deep fade, due to its frequency non-selectivity, the performance of a sub-channel is degraded significantly. Therefore, the entire performance

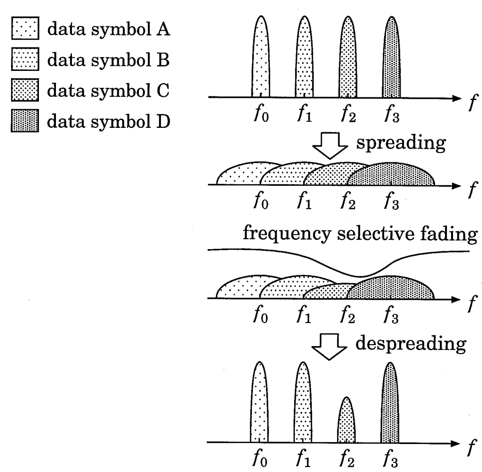


Fig. 2 Power spectrum of an MC-DS-SS signal.

of an MC-DS-CDMA system will be held down in the absence of channel coding. This is regarded as the result of not having path or frequency diversity gain, although the diversity is inherent in wide-band transmission systems including an MC-DS-CDMA system. In order to exploit the inherent diversity, we propose to adopt frequency spread coding in an MC-DS-CDMA system.

2.3 Frequency Spread Coding

In the proposed system, an input sequence at the MC-DS-SS operator $\boldsymbol{X}_i^{(u)}$ is a sequence generated by frequency spread coding instead of a data-symbol sequence. With frequency spread coding, M low-rate data symbols of one user given by a serial to parallel conversion are superimposed with code division multiplexing (CDM) using codes of length M, and then a sequence of the resulting superimposed chips is serial to parallel converted into M frequency sub-channels as shown in Fig.3 [15], [16]. In a sense, M data symbols of one user are superimposed with CDM using codes in frequency domain. Consequently each data symbol is spread over M frequency sub-channels. If these frequency sub-channels are affected differently due to frequency selective fading, a diversity gain can be obtained because M replicas per data symbol will be like Fig.4 after transmission. For the remainder of this paper, the sub-channel carrying M replicas of the same data symbol is denoted as a "sub-code channel," and the code which specifies the sub-code channel and is used for the CDM operation is denoted as a "sub-code." The set of sub-codes is used in all users in common.

The sequence generated by the CDM operation is generally a multi-amplitude sequence which consists of M superimposed chips. For the remainder, the multi-amplitude sequence is referred to as a "CDM block," and each superimposed chip is referred to as a "CDM chip"; accordingly a CDM chip of user u can be given by

$$D_{n,j}^{(u)} = \sum_{m=0}^{M-1} d_{m,j}^{(u)} \, a_{m,n}, \quad n = 0, 1, \ldots, M-1, \tag{12}$$

where $d_{m,j}^{(u)} \in \{\pm 1 \pm j1\}$ represents the data symbol of user u fed to the m-th sub-code channel which has data symbol duration MT_d, the subscript j represents the index of the CDM block, and $a_{m,n} \in \{-1, +1\}$ denotes the n-th chip of the m-th sub-code of length M. We use vectors $\boldsymbol{D}_j^{(u)}$, $\boldsymbol{d}_j^{(u)}$, and $\boldsymbol{a}_m$ to denote the j-th CDM block, the j-th data-symbol sequence to be superimposed, and the m-th sub-code, respectively, i.e.,

$$\boldsymbol{D}_j^{(u)} = \left(D_{0,j}^{(u)}, D_{1,j}^{(u)}, \ldots, D_{M-1,j}^{(u)}\right), \tag{13}$$

$$\boldsymbol{d}_j^{(u)} = \left(d_{0,j}^{(u)}, d_{1,j}^{(u)}, \ldots, d_{M-1,j}^{(u)}\right), \tag{14}$$

and

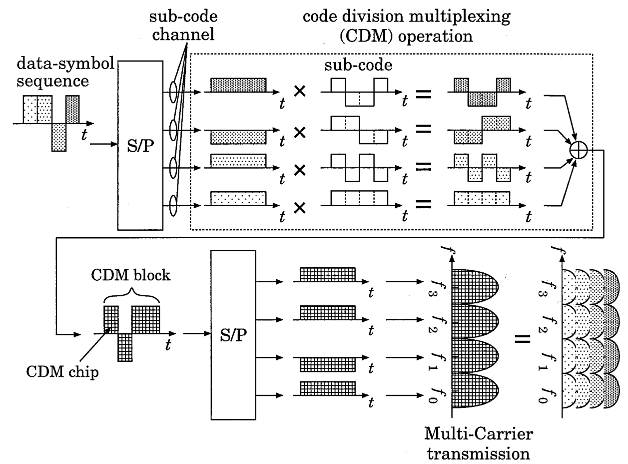


Fig. 3 Principle of frequency spread coding and the power spectrum of the transmitted signal.

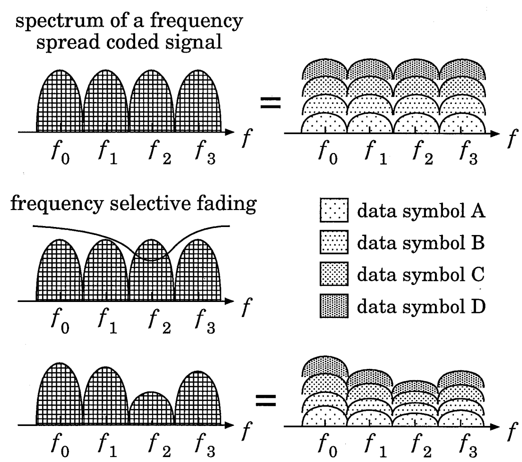


Fig. 4 Power spectrum of a frequency spread coded signal (the same pattern indicates the same data symbol).

$$\boldsymbol{a}_m = (a_{m,0}, a_{m,1}, \ldots, a_{m,M-1}). \tag{15}$$

In this paper, orthogonal Walsh-Hadamard codes are used for the sub-codes. Therefore, the CDM operation and the following serial to parallel conversion can be implemented by an inverse Walsh-Hadamard transform (IWHT).

We note that the bandwidth efficiency is not reduced since M data symbols, each spread over M frequency sub-channels, are superimposed and transmitted with the same frequency sub-channels at the same time. Hence, the Euclidean distance between a sequence of M data symbols before superimposing and that of the M CDM chips produced by frequency spread coding is unchanged, and so frequency spread coding has no ability to correct bit errors in AWGN channels. In consequence, this method can be regarded as not an error-correcting method but a kind of modulation method to exploit frequency diversity without bandwidth expansion.

2.4 Proposed System

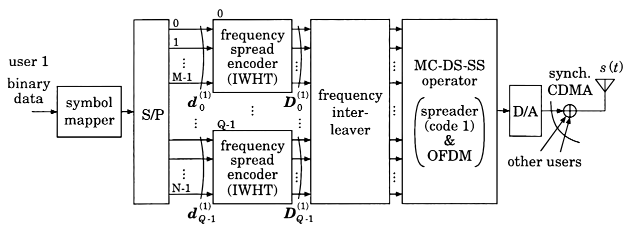
In this subsection, we present a transmission system of an MC-DS-CDMA system which uses frequency spread coding (proposed system) for the down-link.

2.4.1 Transmitter Model

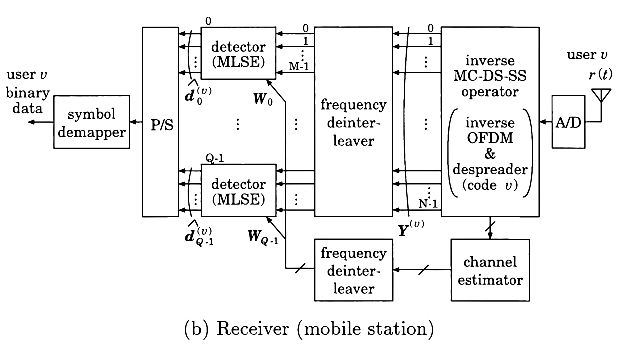
The block diagram of a transmitter (base station) of the proposed system is shown in Fig.5 (a). The transmitter consists of a symbol mapper, frequency spread encoders (IWHT processors), a frequency interleaver, and an MC-DS-SS operator. The frequency spread encoder implements a CDM operation and a serial to parallel conversion of a CDM block described in Fig.3. The base station supplies K users. The binary data of user u, $u = 1, 2, \ldots, K$, are QPSK mapped, yielding complex-valued data symbols each with symbol duration T_d. In the proposed system, after a sequence of the data symbols is serial to parallel converted into $N = QM$ frequency sub-channels, IWHT is implemented on every M data symbols for frequency spread coding. The integer Q is the number of frequency spread encoders. Therefore Q sub-blocks of CDM blocks are transmitted in parallel, and thus $N = QM$ data symbols per user are transmitted simultaneously. Accordingly the i-th sequence of CDM chips generated by frequency spread encoders of user u can be described as

$$\boldsymbol{X}_i^{(u)} = \left(\boldsymbol{D}_{iQ}^{(u)}, \boldsymbol{D}_{iQ+1}^{(u)}, \ldots, \boldsymbol{D}_{(i+1)Q-1}^{(u)}\right), \tag{16}$$

where



(a) Transmitter (base station)



(b) Receiver (mobile station)

Fig. 5 MC-DS-CDMA system using frequency spread coding (proposed system).

$$\boldsymbol{D}_{iQ+q}^{(u)} = \left(D_{0,iQ+q}^{(u)}, D_{1,iQ+q}^{(u)}, \ldots, D_{M-1,iQ+q}^{(u)}\right),$$
$$q = 0, 1, \ldots, Q-1, \tag{17}$$

is a CDM block generated by the q-th frequency spread encoder. The CDM chip on each branch has duration $T_s = NT_d = QMT_d$.

After the frequency spread coding, a frequency interleaver scrambles the CDM chips to achieve low-correlated fading between adjacent CDM chips in a sub-block. For simplicity, the interleaving is not taken into account in the mathematical description. After the interleaving, an MC-DS-SS operation is performed on the CDM chips, and MC-DS-SS symbols are generated. The MC-DS-SS symbols of K users are added synchronously in chips and symbols and are transmitted as an MC-DS-CDMA signal.

2.4.2 Receiver Model

The block diagram of a receiver of the proposed system for mobile station v is presented in Fig.5 (b). On the received signal through a frequency selective fading channel, an inverse MC-DS-SS operation is performed. After frequency deinterleaving, detection of data symbols superimposed with CDM is implemented on every sub-block, which corresponds to decoding of frequency spread coded signals. The detected data symbols are parallel to serial converted and symbol-demapped for yielding binary data.

2.5 Detection Strategy

In the detector, data symbols superimposed with CDM are detected from every CDM block, and decision sequence $\widehat{\boldsymbol{d}}_{iQ+q}^{(v)}$, $q = 0, 1, \ldots, Q-1$, $\forall i$, is obtained. In frequency selective fading channels, the amplitude of each CDM chip of a CDM block is affected by quasi-independent fading, and that makes orthogonality between sub-code channels unreliable. As a result, crosstalk is created between sub-code channels and this degrades the performance.

In order to reduce the effect of this crosstalk, maximum likelihood sequence estimation (MLSE) is used for the detection [15], [16]. The MLSE detector first calculates the likelihood function on all the data sequences, i.e., squared Euclidean distances between the received CDM block and all the candidates which can be transmitted. If QPSK is used, the likelihood function is calculated individually in the I- and Q-channels to reduce complexity of the MLSE.

For simplicity, we restrict attention to a specific CDM block of user v, e.g., $q = 0$, dropping the indexes v, q, and i. The sequence where the detection is implemented, i.e., a CDM block of the 0-th sub-block, is written as

$$\boldsymbol{Y} = \left(Y_0, Y_1, \ldots, Y_{M-1}\right). \tag{18}$$

Let

$$\widehat{\boldsymbol{D}}(\widehat{\boldsymbol{d}}^{I}_{(\kappa)}) = (\widehat{D}^{I}_{0(\kappa)}, \widehat{D}^{I}_{1(\kappa)}, \ldots, \widehat{D}^{I}_{M-1(\kappa)}) \tag{19}$$

be a replica of the CDM block in the I-channel when binary data sequence $\widehat{\boldsymbol{d}}^{I}_{(\kappa)} = (\hat{d}^{I}_{0(\kappa)}, \hat{d}^{I}_{1(\kappa)}, \ldots, \hat{d}^{I}_{M-1(\kappa)})$ is input into a frequency spread encoder as the I-component, where subscript κ, $\kappa = 1, 2, \ldots, 2^M$, represents the index of a candidate for the sequence of binary data and thus of the reference CDM block. Therefore, the n-th element of the reference CDM block κ is given by

$$\widehat{D}^{I}_{n(\kappa)} = \sum_{m=0}^{M-1} \hat{d}^{I}_{m(\kappa)}\, a_{n,m}. \tag{20}$$

The likelihood function for the I-channel can be expressed as

$$\Lambda^{I}_{(\kappa)} = \sum_{n=0}^{M-1} \left| \Re[Y_n] - W_n \widehat{D}^{I}_{n(\kappa)} \right|^2, \tag{21}$$

where $\Re[\cdot]$ denotes the real part of a complex-value and W_n is a weight for the n-th element of the reference CDM block, which is given by

$$W_n = \frac{1}{L} \sum_{l=0}^{L-1} |\widehat{H}_{n,l}|. \tag{22}$$

This is an envelope level of the frequency sub-channel averaged over interval T_s which corresponds to the duration of an MC-DS-SS symbol. Suppose $\kappa = \hat{\kappa}$ gives the minimum of $\Lambda^{I}_{(\kappa)}$, i.e., $\Lambda^{I}_{(\hat{\kappa})} = \min_{\kappa} \Lambda^{I}_{(\kappa)}$, and then $\widehat{\boldsymbol{d}}^{I}_{(\hat{\kappa})}$ is determined as the I-component of the data sequence $\widehat{\boldsymbol{d}}$. Also for the Q-component, a sequence of binary data is determined in the same process. Since the number of all the candidates for each I- or Q-component is 2^M, its complexity increases exponentially as the number of sub-code channels M increases. In this paper, $M \leq 8$ is considered as the limit of practical use.

3. Computer Simulation Results

Performance of the proposed system is evaluated using computer simulation. All the simulation results are considered in the synchronized down-link of a single cell environment. Simulation parameters are shown in Table 1. The root mean square (rms) delay spread τ_{rms} normalized by the MC-DS-SS chip duration is assumed to be $\tau_{rms}/T_c \approx 7.58 \times 10^{-3}$. The maximum Doppler frequency f_D normalized by the MC-DS-SS chip duration is assumed to be $f_D T_c \approx 7.81 \times 10^{-5}$. This value shows the channel parameters are constant over several consecutive MC-DS-SS chip intervals. If the radio transmission bit rate is 512[kbps], the rms delay spread is $\tau_{rms} \approx 59.2$[nsec] which is a typical value in an indoor wireless channel [17] and the maximum Doppler frequency is $f_D \approx 10$ [Hz]. In the computer simulation, perfect channel estimation is assumed.

Table 1 Simulation parameters.

Data modulation	QPSK
Number of sub-carriers N	64
Processing gain L	32
Spreading codes	Walsh-Hadamard codes
Guard interval Δ	$T_c/33$

3.1 Effect of Frequency Spread Coding

In Figs. 6 and 7, the BER performance versus E_b/N_0

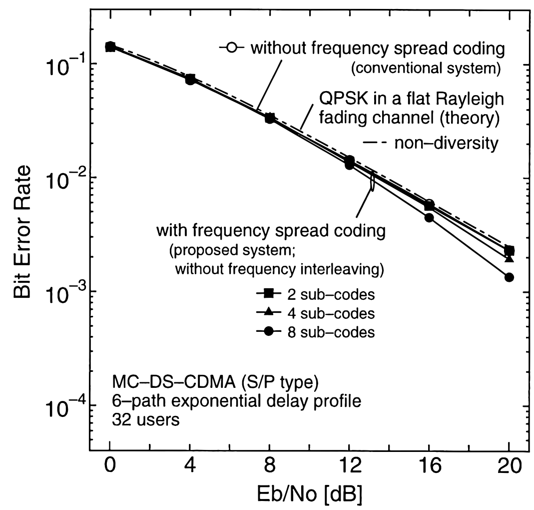


Fig. 6 Bit error rate performance versus E_b/N_0 for the conventional and proposed MC-DS-CDMA systems; without frequency interleaving (in the proposed system); fully loaded system ($K = 32$ users).

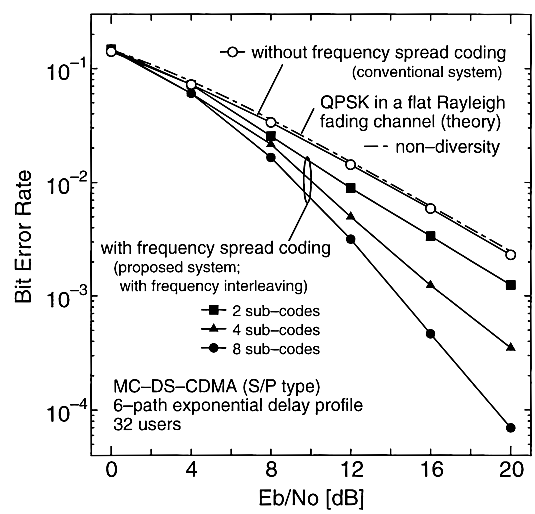


Fig. 7 Bit error rate performance versus E_b/N_0 for the conventional and proposed MC-DS-CDMA systems; with frequency interleaving (in the proposed system); fully loaded system ($K = 32$ users).

of the proposed MC-DS-CDMA system is compared with that of the conventional one. Where E_b and $N_0/2$ represent the average received energy per bit and the two-sided noise power spectral density, respectively. Error-correction coding such as block or convolutional coding is not used for both systems. A fully loaded system, i.e., a system comprising $K = 32$ users, is considered. The channel model is treated with a 6-path exponential power delay profile. Each path fluctuates independently with Rayleigh distribution. The duration between paths is assumed to be stationarily $T_c/132$. Therefore, the maximum delay spread is $\tau_{max} = 5T_c/132$. The average received power ratio of the 6-th path to the first path is about -19.4[dB].

The BERs of the proposed systems without and with frequency interleaving are shown in Figs. 6 and 7, respectively. The frequency interleaver operates as shown in Fig. 8. We denote sub-carriers which transmit the replicas of the same data bit as "identical-bit carriers" [11]. The frequency separation between any two successive identical-bit carriers is maximized. The correlation at any instant of time between the fade envelopes of the i-th and j-th sub-carriers is given by [18]

$$\rho(F) = \frac{1}{1 + \left(|f_i - f_j|\tau_{rms}\right)^2} = \frac{1}{1 + \left(\dfrac{F}{t_c}\tau_{rms}\right)^2}, \tag{23}$$

where $F = |i - j|$. Table 2 shows the correlation between the fade envelopes of adjacent identical-bit carriers ρ_{max} and that of most separated identical-bit carriers ρ_{min}.

Figures 6 and 7 show that the BER performance of the conventional system coincides with the theoretical performance of a QPSK/coherent detection system without diversity in a flat Rayleigh fading channel. Therefore we can see that the conventional system can not obtain a diversity gain although the effect of ICI is eliminated. Figure 6 shows that the BER performance of the proposed system without frequency interleaving is similar to that of the conventional system for any number of sub-code channels M. This result means a frequency diversity gain is not obtained due to high correlation between the fade envelopes of identical-bit carriers as shown in Table 2 (a). On the other hand, Fig. 7 shows the BER performance of the proposed system with frequency interleaving becomes better than that of the conventional one. This result means that the proposed system with frequency interleaving can obtain a frequency diversity gain by using frequency spread coding. The BER performance improves as the number of sub-code channels M increases because larger M gives lower ρ_{min} as shown in Table 2 (b). From this result, we can see ρ_{min} is an important parameter for the effect of frequency spread coding.

In the proposed system, the signal power is concentrated in a certain CDM chip depending on the combination of data symbols. For example, $\boldsymbol{D}_i^{(u)} = \big(M + jM, 0, \ldots, 0\big)$ if data symbols of the i-th data-symbol sequence of user u are all $+1 + j1$. If the CDM chip in which the signal power is concentrated is affected by severe fading, all of data would be damaged. In order to show the effect of the combination of data symbols, computer simulation is carried out in the case that the data symbols are all $+1 + j1$. The result is shown in Fig. 9. In the proposed system, 8 sub-code channels with frequency interleaving is used. Single user system is considered. As shown in this figure, frequency diversity gain is obtained even in this case. However, the diversity gain is reduced as compared with the performance when the random data-symbol sequence is transmitted. Therefore, we can see the BER performance of the proposed system depends on the combination of data symbols.

3.2 Comparison with Different CDMA Systems

We investigate the comparison between the proposed system and the other CDMA systems. As one of the systems compared, an MC-CDMA (copy type) system is investigated. A single-user detection strategy using minimum mean square error (MMSE) equalization [7] is used in the computer simulation. The proposed system

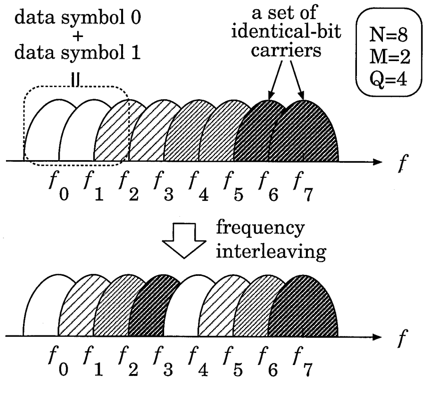


Fig. 8 Frequency interleaving ($N = 8$, $M = 2$, $Q = 4$).

Table 2 Correlation between the fade envelopes of identical-bit carriers.

(a) without frequency interleaving

	$M = 2$	$M = 4$	$M = 8$
ρ_{max}	1.00 ($F = 1$)	1.00 ($F = 1$)	1.00 ($F = 1$)
ρ_{min}	($=\rho_{max}$)	0.999 ($F = 3$)	0.997 ($F = 7$)

(b) with frequency interleaving

	$M = 2$	$M = 4$	$M = 8$
ρ_{max}	0.941 ($F = 32$)	0.985 ($F = 16$)	0.996 ($F = 8$)
ρ_{min}	($=\rho_{max}$)	0.877 ($F = 48$)	0.839 ($F = 56$)

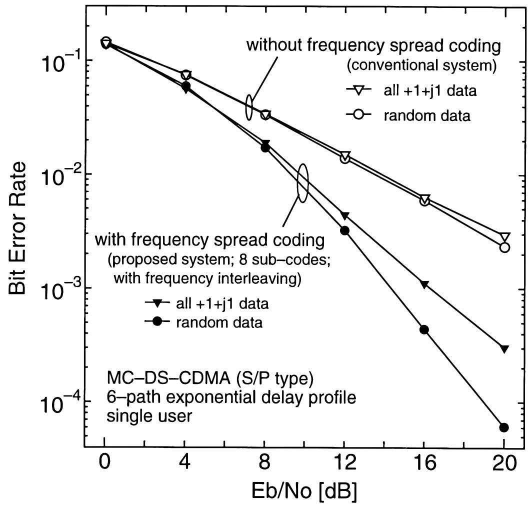


Fig. 9 Bit error rate performance versus E_b/N_0 for the conventional and proposed MC-DS-CDMA systems; 8 sub-code channels with frequency interleaving (in the proposed system); single user ($K = 1$).

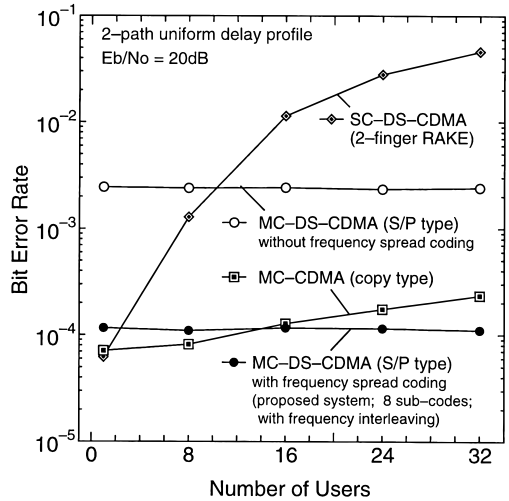


Fig. 10 Bit error rate performance versus number of users for different CDMA systems; $E_b/N_0 = 20$[dB].

is also compared with an SC-DS-CDMA system using a full-finger RAKE receiver. In the computer simulation, a concatenated code [19] which is a combination of a user specific Walsh-Hadamard code and a common long M-sequence of period $2^{21} - 1$ is used for each user in the SC-DS-CDMA system. The radio channel is treated with a two-path model for simplicity of the computer simulation. Each path experiences uncorrelated Rayleigh fading and the average power of the two paths is identical.

Figure 10 shows the BER performance versus the number of users for the conventional and proposed MC-DS-CDMA (S/P type) systems, the MC-CDMA (copy type) system, and the SC-DS-CDMA system. We can see that the performance of the MC-CDMA (copy type) and the SC-DS-CDMA systems is degraded as the number of users is increased because of MAI. On the other hand, the performance of the conventional and proposed MC-DS-CDMA (S/P type) systems is independent on the number of users because the orthogonality between users is ideally kept in the down-link in a cell. In addition, we can see that the performance of the proposed system with $M = 8$ sub-code channels is better than that of the other systems when the number of users is more than 16.

However, the structure of the proposed system is more complex than the other systems compared. Although the proposed system can be realized with an even simpler architecture using only one frequency spread encoder in the transmitter and one MLSE detector in the receiver, it is still complex. Especially, the complexity of MLSE calculation increases exponentially as the number of sub-code channels increases. If we use 8 sub-code channels and QPSK is used, the number of MLSE calculation is 512 to detect 16[bits].

4. Conclusion

This paper has presented an MC-DS-CDMA (S/P type) system which uses frequency spread coding to obtain the inherent frequency diversity gain without additional redundancy. Frequency spread coding is a frequency diversity method in the form of coding. Computer simulation results show that the proposed system needs frequency interleaving to obtain a frequency diversity gain. The proposed system with frequency interleaving can achieve better performance than an MC-DS-CDMA system without frequency spread coding. Furthermore, the proposed system was compared with an MC-CDMA (copy type) system using MMSE equalization and an SC-DS-CDMA system using a RAKE receiver. The result shows that the proposed system is effective when the system load is heavy. The computer simulation result in a two-path Rayleigh fading channel, the proposed system can achieve BER of 1.4×10^{-4} at $E_b/N_0 = 20$[dB] when the system is loaded full, while the MC-CDMA (copy type) and the SC-DS-CDMA systems achieve BERs of 2.3×10^{-4} and 4.6×10^{-2} respectively. Therefore, the proposed system is appropriate for a confirmedly heavy load system in a frequency selective fading channel. However, simplification is a problem which confronts us.

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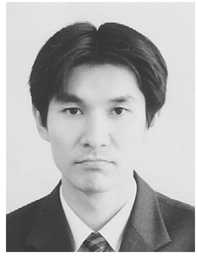

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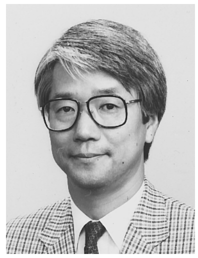

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