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Performance of a Modified Multicarrier Direct Sequence CDMA System

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ABSTRACT

In this paper, we present an improved multicarrier direct sequence (DS) code division multiple access (CDMA) scheme by modifying the system originally proposed by Kondo and Milstein [13]. In this modified system, different spreading sequences multiplied by a data sequence modulate different carriers. This is to prevent the multiple access capability from reducing when the fading characteristics of different carrier frequencies are highly correlated. We have derived a formula which determines the mean values of the relative received signal strength in a single carrier DS CDMA rake system and in a multicarrier DS-CDMA system. We present results on the comparison of the bit error rate (BER) performance of the two systems including the effect of correlation between fading characteristics of different frequencies under various multipath fading conditions. The results indicate that with 50 users the modified multicarrier DS CDMA system can achieve an uncoded irreducible BER of 1.7×10^{-3} with an average received signal-to-noise ratio per bit of 10 dB, which is better than 3.0×10^{-3} achieved by the single carrier DS CDMA rake system, and also show that if multicarrier CDMA system is used with respect to single carrier CDMA system, the SNR gain is up to 4.5 dB for the uncode BER of 10^{-3} being achieved.

I. INTRODUCTION

Recently, several wide band code division multiple access (CDMA) systems have been proposed either to realize an overlay system or to combat multipath [1]-[4], [13]. A multicarrier direct sequence (DS) CDMA system can be considered as one of realization of such a wideband CDMA system [13].

It is well known that the multicarrier DS CDMA system is robust against multipath fading [5]-[10], has a narrow band interference suppression effect [11]-[14] and requires a lower speed, parallel type of signal processing [13].

The multicarrier DS CDMA systems can be categorized into two types [13], the orthogonal frequency division multiplexed (OFDM) system [6]-[10], and the parallel transmission scheme of narrow band DS waveforms in the frequency domain [11]-[13]. In the former system, the individual spectra are not bandlimited and carrier frequencies are chosen to be orthogonal such that the frequency division is achieved, not by band-pass filtering, but by baseband processing [5]. However, this system can not be applicable to the asynchronous CDMA system since signals from other users are no longer orthogonal to the desired signal and multiple access interference increases [13]. On the other hand, in the latter system, the individual spectra are bandlimited and orthogonality among carriers is not required [13]. However, this system requires bank of band-pass filters to transmit and receive the multicarrier signals. The system discussed in this paper belongs to the latter system.

In a recent paper [13], Kondo and Milstein have proposed a new multicarrier DS CDMA system, in which a data sequence multiplied by a spread sequence modulates M carriers and the individual spectra is bandlimited.

Concerning the implementation of the system, all these three multicarrier DS CDMA systems can be implemented by FFT based solutions [18] with some restrictions in selecting PN chip duration and frequency difference between adjacent subchannels. Comparing to the implementation of single carrier DS CDMA system using a rake receiver, the multicarrier DS CDMA system has the same complexity, however, it needs lower speed devices, consequently, low-power consumed devices.

In the paper [13], it has been shown that both of a single carrier CDMA and the multicarrier CDMA systems have the same performance in the absence of partial band interference under the Rayleigh fading channels, in which the delay intensity profile is rectangular and all the carriers see independently fading channels.

Ziemer and Nadgauda [15] have extended the analysis of the multicarrier DS CDMA system to include the effect of correlation between fading characteristics of different carrier frequencies and showed that it is advantageous to space the carriers closer than allowed for independent fading channels, but at the expense of multiple access capability. However, in [15], they didn't try to compare the performance of the multicarrier DS CDMA system with that of a single carrier DS CDMA rake system including the effect of correlation between fading channel characteristics at different carrier frequencies.

In the system proposed in [13], the multiple access interference components of the despreader outputs operating at different carrier frequencies are correlated, that is $E\{\xi_{k,\,i}\ \ \xi_{k,\,j}\} \neq 0$ for $i \neq j$ in the equation (15) of [13], when the fading characteristics of different carriers are correlated and we use DFT (discrete Fourier Transform) technique to implement multicarrier CDMA system such that there is a certain relation between phases of different carriers. Due to this feature, the multiple access capability of the system of [13] is susceptible to the correlation between fading characteristics of different carriers. Also Kondo and Milstein [13] proposed a solution to further ensure independence, in which for decorrelating the sub-carriers one can use sufficient interleaving. However, in this case, the deinterleaver should perform the maximum ratio combing and this makes the system very complicated.

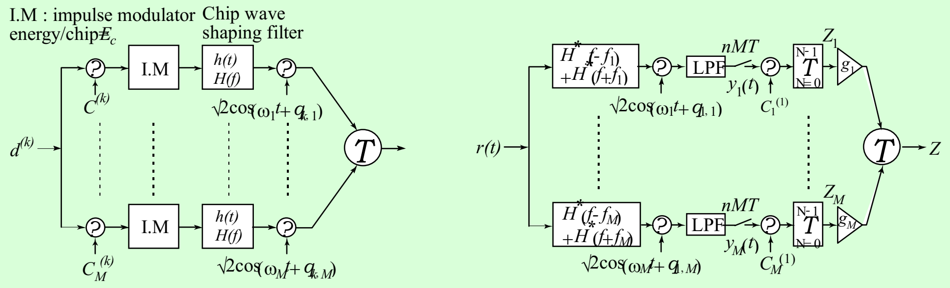
In this paper, we propose a modified multicarrier DS CDMA system which is advantageous at no expense of multiple access capability to space the carriers closer than allowed for independent fading channels. And we compare the performance of the proposed system with that of a single carrier DS CDMA rake system including the effect of correlation between fading characteristics of carrier frequencies.

Section II describes our modified multicarrier DS CDMA system. In Section III, the basic assumptions and conditions for the performance comparison of the proposed system and a single carrier DS CDMA Rake system are described and the probability density functions of the received signal-to-noise ratio are derived. In Section IV, we evaluate the bit error probabilities of both systems. Section V presents several numerical results and finally the conclusions are given in Section VI.

II. SYSTEM MODEL

To make sure that the multiple access interference components of the despreader outputs operating at different carrier frequencies are not correlated, we slightly modified the multicarrier DS CDMA system proposed in [13].

Fig. 1(a) and (b) show the block diagrams of the transmitter and the receiver of the modified multicarrier DS CDMA system. In this system, k th user uses different spreading sequences, ${c_1}^{(k)}, {c_2}^{(k)}, \cdots, {c_M}^{(k)}$, for spreading a data sequence, $d^{(k)}$ with modulating carriers, $\omega_1, \omega_2, \cdots, \omega_M$. Since



(a) (b)

Fig. 1. Block diagrams for (a) transmitter for kth user and (b) receiver for the first user.

correlation between different PN code pairs can be assumed to be independent, we can assume that the multiple access interference components of the despreader outputs at different carrier frequencies are independent.

The chip wave shaping filter in Fig. 1(a) band-limits the DS waveforms such that the DS waveforms do not overlap.

III. PROBABILITY DENSITY FUNCTIONS OF THE RECEIVED SIGNAL-TO-NOISE RATIO

1. Assumptions

To make the performance analysis of both systems simple, we assume that the multiple access interference is taken to be Gaussian. This assumption makes it easy to get a closed form of bit error probability for no diversity in Rayleigh fading [16].

The channel is assumed to be a slowly varying frequency selective Rayleigh fading channel with delay spread of T_m. The delay intensity profile is assumed to be decreased exponentially as delay time increases. As in most radio transmission media, the channel is assumed to be uncorrelated scattering [16].

The normalized delay intensity profile is given by

$$f_p(t) = \exp\left(-\frac{t}{T_m}\right) \tag{1}$$

and the normalized spaced-frequency correlation function is obtained from its Fourier transform as follows:

$$\begin{aligned} |F_p(\triangle f)| &= \frac{\int_0^\infty f_p(t)e^{-j2\pi\triangle f t}dt}{\int_0^\infty f_p(t)dt} \\ &= \frac{1}{\sqrt{(2\pi\triangle f\cdot T_m)^2+1}} \end{aligned} \tag{2}$$

2. Received Signal-to-Noise Ratio

The single carrier DS CDMA rake system has a rake receiver with the maximum arms and the multicarrier DS CDMA system has carriers.

The received signal-to-noise ratios as a result of maximum ratio combining performed in single carrier DS CDMA rake system and in multicarrier DS CDMA system can be obtained directly from [13]. For the single carrier DS CDMA rake system, it is given by

$$\widehat{\gamma}=\frac{N_1{}^2E_{c1}\sum_{i=1}^{M}\widehat{z}_i}{\widehat{\sigma}^2}, \tag{3}$$

where $\widehat{z}_i$ is the relative received signal intensity of ith arm of the rake receiver, N_1 is the number of PN chips per symbol, E_{c1} is the energy per PN chip, and $\widehat{\sigma}^2$ is the conditional variance of the received noise conditioned upon $\widehat{z}_i$. Since the $\widehat{z}_i$ is the square of received signal amplitude which is Rayleigh distributed, the $\widehat{z}_i$ has an exponential distributed and $\{\widehat{z}_i\}$ are independent and not necessarily identically distributed. For the multicarrier DS CDMA system, it is given by

$$\gamma=N^2E_c\sum_{i=1}^{M}\frac{z_i}{\sigma_i{}^2}, \tag{4}$$

where z_i is the relative received signal intensity of ith sub-channel, N is the number of PN chips per symbol of sub-carrier, E_c are the energy per PN chip per sub-carrier, and $\sigma_i{}^2$ is the conditional variance of the received noise from the ith sub-channel conditioned upon z_i.

We don't consider the effect of the partial band interference since it is evident from the result of [13] that multicarrier DS CDMA system is superior to the single carrier DS CDMA rake system in the presence of partial band interference. Then the received noise variance of different subchannels have same value of σ^2, and the equation of (4) can be rewritten as

$$\gamma=\frac{N^2E_c\sum_{i=1}^{M}z_i}{\sigma^2}. \tag{5}$$

Since the z_i is the square of received signal amplitude which is Rayleigh distributed, the z_i has an exponential distributed and are identical and $\{z_i\}$ not necessarily independently distributed.

3. Probability Density Function of the Relative Received Signal Intensity

The probability density function of $\widehat{z}_i$ is

$$P_{\widehat{z}_i}(\widehat{z}_i)=\frac{1}{\widehat{\eta}_i}\exp\left(-\frac{\widehat{z}_i}{\widehat{\eta}_i}\right), \tag{6}$$

where $\widehat{\eta}_i$ is the mean value of $\widehat{z}_i$. We can obtain the probability density function of $\widehat{z}=\sum_{i=1}^{M}\widehat{z}_i$ directly from [13] and [16] as follows:

$$P_{\widehat{z}_i}(\widehat{z})=\sum_{i=1}^{M}\frac{\widehat{v}_i}{\widehat{\eta}_i}\exp\left(-\frac{\widehat{z}}{\widehat{\eta}_i}\right), \tag{7}$$

where

$$\widehat{v}_i=\prod_{\substack{n=1\\ n\neq i}}^{M}=\frac{\widehat{\eta}_i}{\widehat{\eta}_i-\widehat{\eta}_n}. \tag{8}$$

The probability density function of z_i is also given by

$$P_{z_i}(z_i) = \frac{1}{\eta}\exp\left(-\frac{z_i}{\eta}\right), \tag{9}$$

where $\{z_i\}$ have equal mean value of η since they are identically distributed.

The moment generating function of $z = \sum_{i=1}^{M} z_i$ is given by [17]

$$\Phi_z(s) = \frac{1}{\det(\mathrm{I}+s\mathrm{C})} = \prod_{i=1}^{M} \frac{1}{(1+s\lambda_i)}, \tag{10}$$

where C is the covariance matrix of $\{\sqrt{z_i}\}, \lambda_i$ is its eigenvalue, and I is the identity matrix.

The probability density function of z is the inverse Laplace transform of $\Phi_z(s)$ and, if $\lambda_i \neq \lambda_j$ for $i \neq j$, it is given by

$$P_z(z) = \sum_{i=1}^{M} \frac{v_i}{\lambda_i}\exp\left(-\frac{z}{\lambda_i}\right), \tag{11}$$

where

$$v_i = \prod_{\substack{n=1\\ n\neq i}}^{M} \frac{\lambda_i}{\lambda_i - \lambda_n}. \tag{12}$$

The equation (11) is same as the equation (6) of [15].

4. Conditions for Performance Comparison

As in [13], for the performance comparison, we should ensure that both systems receive the same average energy per symbol, E_b. Since $E_b = MNE_c = N_1E_{c1}$ from (3) and (5), $E\{\sum_{i=1}^{M} z_i\}/M$ should be equal to $E\{\sum_{i=1}^{M} \widehat{z}_i\}$.

In this paper we set

$$E\left\{\frac{1}{M}\sum_{i=1}^{M} z_i\right\} = E\left\{\sum_{i=1}^{M} \widehat{z}_i\right\} \equiv 1. \tag{13}$$

At this point, we should carefully choose the mean values of $\widehat{\eta}_i$ and η such that the condition of (13) is satisfied. Since $\{\widehat{z}_i\}$ are independent, the mean value of $\widehat{z}_i$ is the sample value of the normalized delay intensity profile $f_p(t)$ and can be easily obtained as follows:

$$\widehat{\eta}_i = \frac{f_p((i-1)T_c)}{\sum_{k=1}^{M} f_p((k-1)T_c)}, \tag{14}$$

where T_c, the chip duration of the single carrier DS CDMA system is given by $T_c = (1+\alpha)/BW$. In this, BW is the bandwidth of the single carrier DS CDMA rake system and α is the filtering roll-off factor.

The mean value of z_i can be obtained from the spaced-frequency correlation function of the given delay intensity profile.

Since $F_p(\triangle f)$ is the correlation coefficient between two sub-carriers separated by $\triangle f$ and $\sigma_\alpha{}^2 = \eta(1-\pi/4)$ is the variance of $\sqrt{z_i}$, the elements of covariance of matrix of $\{\sqrt{z_i}\}$, $C_{i,j}$, is simply given by

$$C_{i,j} = \sigma_\alpha{}^2 \cdot F_p(\mid i-j \mid \cdot B_m), \tag{15}$$

where B_m is the frequency separation between adjacent sub-carriers. To ensure that both systems use the same total bandwidth, we set $B_m = BW/M$.

From (15), the eigenvalue of the covariance matrix has a relation of $\lambda_i =$

${\sigma_\alpha}^2 \cdot \{\lambda_i\}_{{\sigma_\alpha}^2=1}$ and therefore, the mean of z, $E\{z\}$, can be written as follows:

$$\begin{aligned} E\{z\} &= \sum_{i=1}^{m} \pi_i \cdot \lambda_i \\ &= {\sigma_\alpha}^2 \cdot \left\{ \sum_{i=1}^{M} \pi_i \cdot \lambda_i \right\}_{{\sigma_\alpha}^2=1} \\ &= {\sigma_\alpha}^2 \cdot \{E\{z\}\}_{{\sigma_\alpha}^2=1} \end{aligned} \quad . \qquad (16)$$

From (13) and (16), η can be obtained as follows:

$$\eta = \frac{M}{\left(1-\frac{\pi}{4}\right)\cdot\{E\{z\}\}_{\eta=1/(1-\pi/4)}}. \qquad (17)$$

For $\eta = 1/(1-\pi/4)$, the elements of the covariance matrix are the same as the correlation coefficients which will be directly obtained from the spaced frequency correlation function.

IV. EVALUATION OF BIT ERROR PROBABILITY

We can use the formula for obtaining the BER performance of a BPSK system in fading channel evaluated in [13] as a conditional probability of bit error of both systems conditioned upon $\widehat{z}$ or z. The conditional probability of bit error probability is given by

$$P_b(\gamma_b) = \phi(-\sqrt{\gamma_b}), \qquad (18)$$

where

$$\phi(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-t^2/2} dt \qquad (19)$$

and γ_b is the received signal to noise ratio of a rake receiver in the single carrier DS CDMA system or a receiver of a carrier in the multicarrier DS CDMA system.

From (3) and (18), the probability of bit error for single carrier DS CDMA rake system is given by

$$P_{e,s} = \int_0^\infty \phi\left(-\sqrt{\frac{{N_1}^2 E_{c1}\,\widehat{z}}{\widehat{\sigma}^2}}\right) p_{\widehat{z}}(\widehat{z})\,d\,\widehat{z} \qquad (20)$$

and from (5) and (18), the probability of bit error for multicarrier DS CDMA system is given by

$$P_{e,m} = \int_0^\infty \phi\left(-\sqrt{\frac{N^2 E_c z}{\sigma^2}}\right) p_z(z)\,dz. \qquad (21)$$

From (20) and (21), the closed forms of the probability of bit error for both of two systems can be obtained as follows:

$$P_{e,s} = \frac{1}{2}\left[1-\sum_{i=1}^{M} \widehat{v}_i \cdot \sqrt{\frac{2{N_1}^2 E_{c1}\,\widehat{\eta_i}^2\,/\,\widehat{\sigma}^2}{4+2{N_1}^2 E_{c1}\,\widehat{\eta_i}^2\,/\,\widehat{\sigma}^2}}\right] \qquad (22)$$

for single carrier DS CDMA rake system, and

$$P_{e,m} = \frac{1}{2}\left[1-\sum_{i=1}^{M} \widehat{v}_i \cdot \sqrt{\frac{2N^2 E_c \lambda_i/\sigma^2}{4+2N^2 E_c \lambda_i/\sigma^2}}\right] \qquad (23)$$

for multicarrier DS CDMA system.

Again, since correlation between different PN code pairs can be assumed to be independent, we can assume that the multiple access interference components of the despreader outputs at different carrier frequencies are independent even though the fading characteristics of different carriers are highly correlated. Therefore, we don't need to take into account the correlation coefficients between multiple access interference at different carriers. Then, we can directly use variances of the noise and multiple access interference evaluated in [13].

V. NUMERICAL RESULTS

From Fig. 2 and Fig. 3, it is evident that the multicarrier DS CDMA system becomes superior to the single carrier DS CDMA rake system when $0 < BW \cdot T_m < M$. In Fig. 2, where $M = 4$, $K = 1$ and $BW \cdot T_m = 0.5$, note that multicarrier CDMA system requires E_b/N_0 of 12.5 dB to achieve uncoded BER of 10^{-3}, whereas the single carrier CDMA system requires 17 dB. For another example, consider the curves in Fig. 3, where $E_b/N_0 = 20$ (dB), $M = 4$, and $K = 1$. Note that both systems have same BER of 3×10^{-7} when $BW \cdot T_m > 4$, but when $BW \cdot T_m = 0.5$, the BER of the multicarrier DS CDMA system is 7.8×10^{-7}, while that of single carrier DS CDMA rake system is 1.1×10^{-5}. This means the multicarrier DS CDMA system is more robust than a single carrier DS CDMA rake system to the variation of fading channel characteristics. The reason for this can be found in the comparison of probability density functions of $\widehat{z}$ and z/M. As shown in Fig. 4, we observe that the smaller $BW \cdot T_m$ is, the larger variances of both random variables are. However, the variance of $\widehat{z}$ is larger than that of z/M. Due to this, the BER of single carrier DS CDMA rake system is higher than that of the multicarrier DS CDMA system.

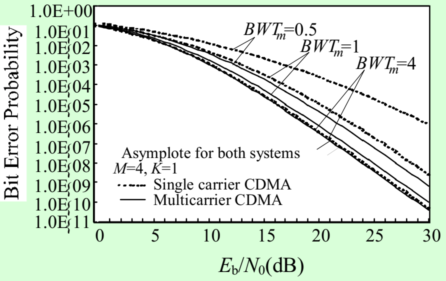


Fig. 2. BER vs. E_b/N_0 for $\alpha = 0.5$, $M = 4$ and $K = 1$.

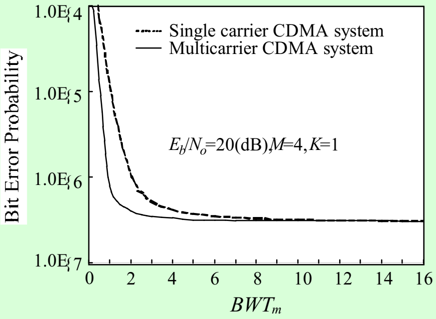
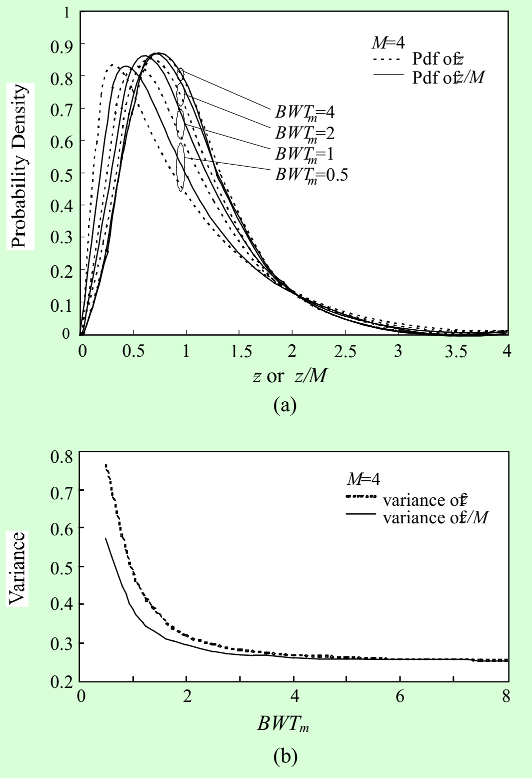


Fig. 3. BER vs. $BW \cdot T_m$ for $\alpha = 0.5$, $E_b/N_0 = 20$(dB), $M = 4$, and $K = 1$.

In the frequency non-selective fading channel, that is $BW \cdot T_m = 0$, two systems have the same performance since there is no frequency diversity gain in the multicarrier DS CDMA system and no multipath diversity gain in single carrier DS CDMA rake system.

Fig. 5 shows that the additional diver-



(a)

(b)

Fig. 4. (a) Probability Density Functions and (b) variances of $\widehat{z}$ and z/M for $M = 4$.

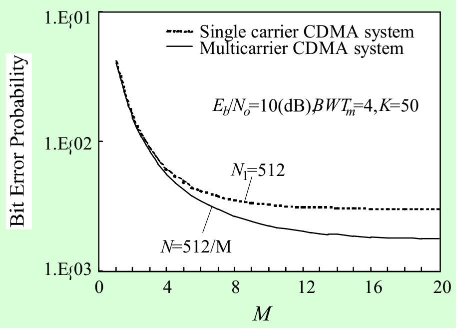


Fig. 5. BER vs. M for $\alpha = 0.5$, $E_b/N_0 = 10$(dB), $K = 50$ and $BW \cdot T_m = 4$.

sity gain can be achieved with more carriers in the multicarrier DS CDMA system or with more rake receivers in the single carrier DS CDMA rake system. However, with the similar reason mentioned above, the multicarrier DS CDMA system provides more additional diversity gain than single carrier DS CDMA rake system. As shown in Fig. 5, when $E_b/N_0 = 10$ (dB), 50 users and $BW \cdot T_m = 4$, we can achieve the BER of 1.7×10^{-3} from additional diversity gain with 20 carriers, while we can achieve BER of 3.0×10^{-3} from the additional diversity gain with 20 rake receivers.

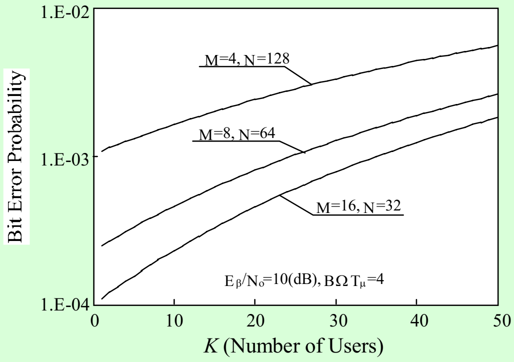


Fig. 6. BER of multicarrier DS CDMA system vs. K, for $\alpha = 0.5$, $E_b/N_0 = 10$(dB), $BW \cdot T_m = 4$, and $M \cdot N = 512$.

In Fig. 6, we show that the modified system can achieve at no expenses of multiple access capability the additional diversity gain with more carriers than allowed for the independent fading channels, while the system proposed in [13] have to pay at the expenses of multiple access capability for achieving additional diversity gain [14]. For example, in Fig. 5, the modified multicarrier DS CDMA system cannot support any users at a BER of 10^{-3} with $E_b/N_0 = 10$ (dB) when the total bandwidth is divided into 4 equi-width frequency bands and the processing gain of each band is 128. However, when it is divided into 16 bands and the processing gain of each band is 32, the system can support about 35 users. In the system proposed in [13], since multiple access interference components of despreader outputs operating at different carrier frequencies are correlated when the fading characteristics of different carriers are correlated, the multiple access capability of the system of [13] is susceptible to the correlation between fading characteristics of different carriers. In the modified system, the multiple access interference received from different sub-channels are independent so that we can get the diversity gain.

VI. CONCLUSION

In this paper, we presented the results of an improved multicarrier DS CDMA system by modifying the model originally proposed by Kondo and Milstein [13]. In this modified system, different spreading sequences multiplied by a data sequence modulate different carriers. This type of signaling makes the multiple access interference with different frequencies independent and prevents the multiple access capability from reducing when the fading characteristics of carrier frequencies are highly correlated. As a result, about 35 users at a BER of 10^{-3} may access the channel simultaneously with $E_b/N_0 = 10$ (dB) with 16-equi-width frequency bands.

We also derived a formula which determines the mean values of the relative received signal intensities in a single carrier DS CDMA rake system and a multicarrier DS CDMA system. This was to compare the performance of two systems including the effect of correlation between fading characteristics of carriers. The results indicate that the modified multicarrier DS CDMA system can achieve an uncoded irreducible BER of 1.7×10^{-3} with $E_b/N_0 = 10$ (dB) in the frequency selective fading channels where $0 < BW \cdot T_m < M$, which is better than 3.0×10^{-3} achieved by the single carrier DS CDMA rake system, and if multicarrier CDMA system is used with respect to single carrier CDMA system, the SNR gain is up to 4.5 dB for the uncode BER of 10^{-3} being achieved. It is also shown that, in the frequency non-selective or the highly selective fading channels, two systems have same BER performance.

These results mean that the modified

multicarrier DS CDMA system provides a mobile user with freedom of mobility more than a single carrier DS CDMA rake system.

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