# Chip-Interleaved Self-Encoded Multiple Access with Iterative Detection in Fading Channels

Youn Seok Kim, Won Mee Jang, Yan Kong, and Lim Nguyen

*Abstract:* **We propose to apply chip interleaving and iterative detection to self-encoded multiple access (SEMA) communications. In SEMA, the spreading code is obtained from user bit information itself without using a pseudo noise code generator. The proposed scheme exploits the inherent diversity in self encoded spread spectrum signals. Chip interleaving not only increases the diversity gain, but also enhances the performance of iterative detection. We employ user-mask and interference cancellation to decouple self-encoded multiuser signals. This paper describes the proposed scheme and analyzes its performance. The analytical and simulation results show that the proposed system can achieve a 3 dB power gain and possess a diversity gain that can yield a significant performance improvement in both Rayleigh and multipath fading channels.**

*Index Terms:* **Chip-interleaving, interference cancellation, iterative detection, self-encoded multiple access (SEMA), spread spectrum.**

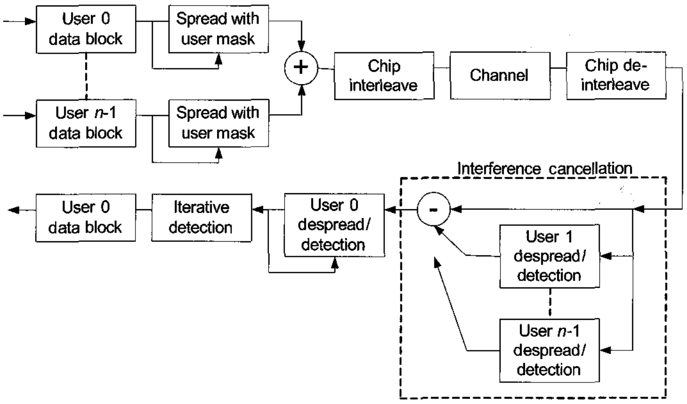

Fig. 1. System transmitter and receiver block diagram.

## I. INTRODUCTION

The fluctuation and attenuation of signals are some of the many challenges in wireless mobile communications. As a result, a great deal of research has been devoted to improving the performance of the direct sequence code division multiple access (DS-CDMA) spread spectrum system in wireless fading channels. Diversity reception can improve the system performance by combining copies of the received signals that have arrived at the receiver at different times due to, for example, the multipath effect of such channels. Diversity scheme not only can increase the overall received signal strength, but also would average out the signal fluctuation. Chip interleaved DS-CDMA [1], [2] is another approach to mitigate the performance degradation by shuffling in time the chips within one bit across different bits. In a time selective fading channel, the interleaved spreading chips will therefore undergo independent fading instead of experiencing the same bit fading factor as would be the case without interleaving. Recently, we have developed an iterative detection scheme based on our work on self-encoded spread spectrum [3]. In self-encoded spread spectrum, the transmitting bit information is used for generating the user spreading sequences [4]. At the transmitter, the current bit is spread by the output of a delay shift register that stores the previous $N$ bits, so that the current bit information would be used in the spreading operation of the next $N$ bits. With iterative detection in the receiver, the estimate of the current bit can therefore be updated as the next $N$ bits are received. This accordingly will result in an overall diversity gain. In this paper, we propose to combine chip interleaved DS-CDMA with iterative detection for self-encoded spread spectrum. The rest of this paper is organized as follows. The system model is developed in Section II and the performance of the proposed system is analyzed in Section III. Section IV presents the simulation.

## II. SYSTEM MODEL

Fig. 1 shows the system block diagram of the transmitter and receiver. The multiple users ($n$ users in the block diagram) generate their own data stream. Each user's data are spread according to the spreading code obtained from the user bit information itself (self-encoded) without using a conventional pseudo noise (PN) code generator. In addition, we apply the user mask to the spread sequence to prevent multiuser crosstalk. After the user spread sequences are added, the chips are read into the interleaving frame ($N \times N$ rectangular array) row by row and read out to the channel column by column to provide the net effect of breaking up any error bursts that occur during the course of data transmission over the wireless channel. After chip de-interleaving at the receiver, the interference signal is despread and the interfering bits are detected for further cancellation of the multiuser interference. Subsequently, the isolated user spread sequence is despread with the previous data bits that were already detected. The user data bits detected by the despreading operation are re-estimated iteratively (iterative detection). Our focus is on the performance enhancement by applying the chip-interleaving to the iterative detection of self-encoded multiple access (SEMA) system.

In this paper, we will consider synchronous self-encoded spread spectrum (SESS) systems employing binary phase-shift

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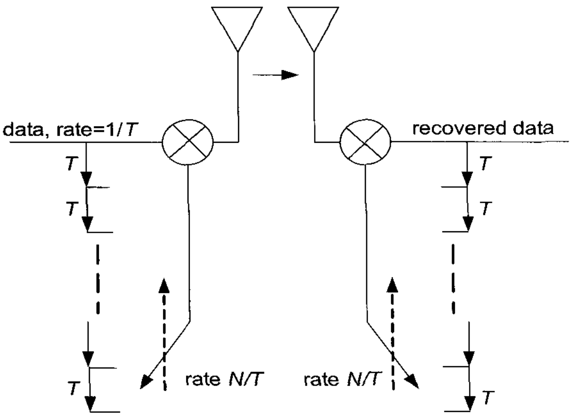

Fig. 2. Self encoded spread spectrum system.

keying (BPSK). As can be seen in Fig. 2, SESS does not use PN spreading codes; in fact the PN code generator had been eliminated at the transmitter. Instead, the length $N$ spreading code has been obtained from the user bit information itself. In the receiver, the user bit is despread using the despreading sequence that has been generated via feedback from $N$ previously recovered bits. However, the feedback despreading code as generated may have chip errors due to detection bit errors. Because of this self interference, the despreading sequence at the receiver may be different from the spreading sequence at the transmitter, thereby causing a performance degradation at low signal to noise ratio (SNR). This effect of self interference is mitigated at high SNR, and the bit error rate becomes similar to that of conventional random spreading systems. In applying chip interleaving to SESS, we consider an $N \times N$ block where $N$ is the spreading length so that there are $N$ bits in a block and each bit is spread sequentially by the self-encoding scheme. Let $\mathbf{b}$ and $e_n$ be the sequence of the user data bits and the corresponding chip information after spreading, respectively. The $N \times N$ block is formed after the $N$-th bit has been spread. Row by row, each spreading sequence is then transmitted following a transpose of this $N \times N$ block;

$$\mathbf{b} = \underbrace{\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_N \end{bmatrix}}_{\text{data block } [N \times 1]} \qquad (1)$$

$$\mathbf{D} = \underbrace{\begin{bmatrix} e_0 & e_{-1} & e_{-2} & \cdots & e_{-N+1} \\ e_1 & e_0 & e_{-1} & \cdots & e_{-N+2} \\ e_2 & e_1 & e_0 & \cdots & e_{-N+3} \\ e_3 & e_2 & e_1 & \cdots & e_{-N+4} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ e_{N-1} & e_{N-2} & e_{N-3} & \cdots & e_0 \end{bmatrix}}_{\text{spread sequence block } [N \times N]} \qquad (2)$$

$$\mathbf{D}^T = \underbrace{\begin{bmatrix} e_0 & e_1 & e_2 & \cdots & e_{N-1} \\ e_{-1} & e_0 & e_1 & \cdots & e_{N-2} \\ e_{-2} & e_{-1} & e_0 & \cdots & e_{N-3} \\ e_{-3} & e_{-2} & e_{-1} & \cdots & e_{-N+4} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ e_{-N+1} & e_{-N+2} & e_{-N+3} & \cdots & e_0 \end{bmatrix}}_{\text{transposed spread sequence block } [N \times N]} . \qquad (3)$$

Assuming that the channel fading is independent from bit to bit, it is clear from the above operation at the transmitter that each row would experience the same fading during a bit interval. At the receiver, the self encoding and chip interleaving operation in the transmitter is reversed. After the sequence information in the $N \times N$ block has been received, the block is transposed again to obtain the original sequence block that contains the user bit information. The feedback despreading operation can then be performed sequentially from the first row to the $N$-th row in the block;

$$[\hat{\mathbf{b}} : \hat{\mathbf{D}}] = \underbrace{\begin{bmatrix} \hat{b}_1 & \hat{e}_0 & \hat{e}_{-1} & \hat{e}_{-2} & \cdots & \hat{e}_{-N+2} & \hat{e}_{-N+1} \\ \hat{b}_2 & \hat{e}_1 & \hat{e}_0 & \hat{e}_{-1} & \cdots & \hat{e}_{-N+3} & \hat{e}_{-N+2} \\ \hat{b}_3 & \hat{e}_2 & \hat{e}_1 & \hat{e}_0 & \cdots & \hat{e}_{-N+4} & \hat{e}_{-N+3} \\ \hat{b}_4 & \hat{e}_3 & \hat{e}_2 & \hat{e}_1 & \cdots & \hat{e}_{-N+5} & \hat{e}_{-N+4} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \hat{b}_N & \hat{e}_{N-1} & \hat{e}_{N-2} & \hat{e}_{N-3} & \cdots & \hat{e}_1 & \hat{e}_0 \end{bmatrix}}_{\text{data output and received spread sequence block } [N \times N]} . \qquad (4)$$

Here $\hat{e}_i$ is the estimated value of $e_i$ at the receiver. An estimate of the $N$ data bits, $\hat{b}_k$, can be obtained following the despreading operation. Now, because of the unique self-encoded operation, the spreading sequences for the next $N$ bits also contain the particular chip that is identical to the current bit. This means the $N$ user bits that have been detected by the despreading operation can be re-estimated iteratively. We observe that such an iterative detector which has linear complexity in $N$ is suboptimal in comparison to the maximum-likelihood sequence estimation (MLSE) receiver which has exponential complexity for self-encoded signals. The iterative detector, however, can exploit the redundancy in the self-encoded signals with only a moderate increase in the computational complexity compared to simple feedback detector. In our system, since the operation of the iterative detector is based on the fact that since $\hat{e}_1$ carries the information of the current data bit $b_1$, the next $N$ chip information from the incoming $N$ bit sequence makes it possible to re-estimate bit $b_1$. That is, the decision variable $r$ of $b_1$ can be written as

$$r = \underbrace{\sum_{k=-N+1}^{0} \hat{e}_k e_k}_{\text{correlation output}} + \underbrace{\sum_{i=2}^{N} \hat{b}_i \hat{e}_1 + \hat{b}_{N+1} \hat{e}_1}_{\text{iterative detection output}} . \qquad (5)$$

We can see that $e_1$ in the $i$-th row of $\mathbf{D}$ will go through the same fading with $b_i$ since the $i$-th row of $\mathbf{D}$ is the spread value of $b_i$.

Notice that we have used the same notation, $e_k$ to denote the estimated despreading sequence although it may differ from the transmitted spread sequence due to possible detection errors at the receiver. It is clear that the number of chips employed by the above iteration in making a bit decision is $2N$ chips instead of $N$ chips. As a result, an improvement in the system performance can be reasonably expected.

## III. PERFORMANCE ANALYSIS

As discussed in the previous section, the iterative detector combines the energy of $2N$ chips to make a bit decision: The first $N$ chips are obtained by despreading current bit with the current spreading sequence, and each of the next $N$ iteration chips are obtained sequentially (from the next $N$ self-encoded spreading sequences) by despreading the following $N$ bits. A significant consequence of this iterative detection scheme is that not only the signal strength can be expected to increase by a factor of two, but there is also an overall diversity gain. The diversity gain comes from the fact that since each transmitting row experiences independent fading, each of the $2N$ iteration chips employed in the detector has also undergone independent fading with a different fading factor for due to chip interleaving and self encoding. Let $e$ be energy of each chip, i.e., $E_b/N$ where $E_b$ is the bit energy. Let the fading factor for the $k$-th iteration chip be $\alpha_k e^{j\phi_k}$ where the channel attenuation, $\alpha_k$, has the Rayleigh distribution, and the phase shift, $\phi_k$, has the uniform distribution in $[0, 2\pi)$ for flat fading channels. We assume that the channel attenuation and the phase shift are known perfectly at the receiver. Since we assume flat fading that is constant over one bit and is independent from bit to bit, each row in $\mathbf{D}^T$ goes through the same fading and each different row has an independent fading. Therefore, $\hat{e}_0, \hat{e}_{-1}, \hat{e}_{-2}, \cdots, \hat{e}_{-N+1}$ in the first row of the matrix in (4) all have an independent fading. This statement corresponds to the first term of (5) and (6). We can also see that $\hat{b}_i$ in the second term of (5) experiences the same fading with $e_1$ in the $i$-th row of $\mathbf{D}$ and also with $e_{-i+2}$ in the first row of $\mathbf{D}$ since each column in $\mathbf{D}$ goes through the same fading. This statement corresponds to the second term of (5) and (6). The result is condensed into (7). Therefore, it is easy to recognize that the iterative detector is equivalent to a maximal ratio combiner whose output can be expressed as a single decision variable in the form ([5], p. 823)

$$e\sum_{k=0}^{N-1}\alpha_k^2 + e\sum_{k=0}^{N-2}\alpha_k^2 + e\alpha_N^2 \tag{6}$$

$$=2e\sum_{k=0}^{N-2}\alpha_k^2 + e\alpha_{N-1}^2 + e\alpha_N^2. \tag{7}$$

Here, we have assumed by chip-interleaving and iterative detection that $\alpha_k$ are i.i.d. Rayleigh random variables. The first term in (6) is from the despread chips of the current bit. The second term in (6) is from each particular self-encoded spreading chip whose value is identical to the current bit that has been stored by the shift register and used in the spreading sequences for the following $N$ bits. Notice that each row of $\mathbf{D}^T$ in (3) experiences the same fading. Therefore, a pair of fading factors in the first and second terms are identical. The last term in (7) comes from the next $N \times N$ block since the particular self-encoded spreading chip that is identical to the current bit would remain until the first row of the next block. Thus, (7) can be approximated as

$$2e\sum_{k=0}^{N-2}\alpha_k^2 + e\alpha_{N-1}^2 + e\alpha_N^2 \approx 2e\sum_{k=0}^{N-1}\alpha_k^2. \tag{8}$$

Let

$$\beta = \sum_{k=0}^{N-1}\alpha_k^2 \tag{9}$$

where $\beta$ is a chi-square distributed random variable with $2N$ degrees of freedom. The conditional error probability can now be expressed straightforwardly as

$$P_{e|\beta} = Q\left(\sqrt{\frac{2\times 2e\beta}{N_o}}\right) = Q\left(\sqrt{\frac{4E_b\beta}{NN_o}}\right). \tag{10}$$

Denoting $p(\beta)$ as the pdf of $\beta$, the average error probability therefore is

$$P_e = \int_0^{\infty} Q\left(\sqrt{\frac{4E_b\beta}{NN_o}}\right)p(\beta)d\beta. \tag{11}$$

The bit error rate of an $N$-fold combined diversity is then given as [5]

$$P_e = \left[\frac{1}{2}(1-\mu)\right]^N \sum_{k=0}^{N-1}\binom{N-1+k}{k}\left[\frac{1}{2}(1+\mu)\right]^k. \tag{12}$$

Here, $\mu$ is defined as

$$\mu = \sqrt{\left(\frac{\bar{\gamma}_c}{1+\bar{\gamma}_c}\right)} \tag{13}$$

where $\bar{\gamma}_c$ is the average chip energy to noise ratio, $\bar{\gamma}_c = 2E_b/(NN_o)$. We have so far analyzed the single-user performance of the proposed self-encoded system with chip-interleaving and iterative detection. In the following, we will consider the multiuser performance of the proposed system. Now in a SEMA system, the multiuser interference may result in a particular multiuser crosstalk problem as follows. In essence, since the spreading code of each user is purely random, these codes may occasionally be sufficiently similar (correlated) among some users. Therefore, the receiver of the desired user may end up tracking the interfering user whose spreading code may happen to be similar to the desired user due to the statistical nature of the random data from the users. Unlike self-interference that is mitigated at high SNR, multi-user crosstalk can persist and therefore requires an additional solution. We propose to employ a user mask to prevent the receiver from erroneously tracking the data from the interfering user. The length of the user mask will be the same as the length of the user spreading codes. However, this mask is unique to each user, and is fixed instead of randomly time varying like the self-encoded spreading sequences. The user mask code modifies the spreading and despreading sequences of each user by means of an XOR operation. The above crosstalk problems therefore can be avoided

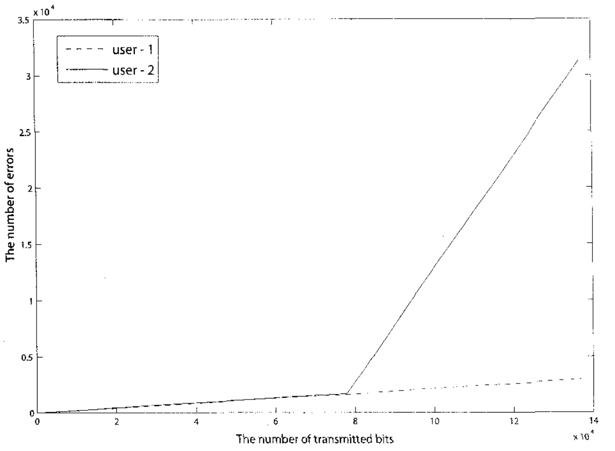

Fig. 3. Two user, self-encoded multiple access, 64 chips/bit, without user mask, AWGN.

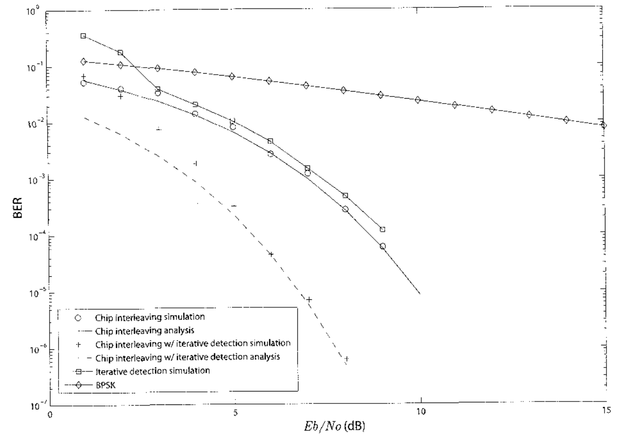

Fig. 5. Analytical and simulation BER, single user, 64 chips/bit, Rayleigh fading.

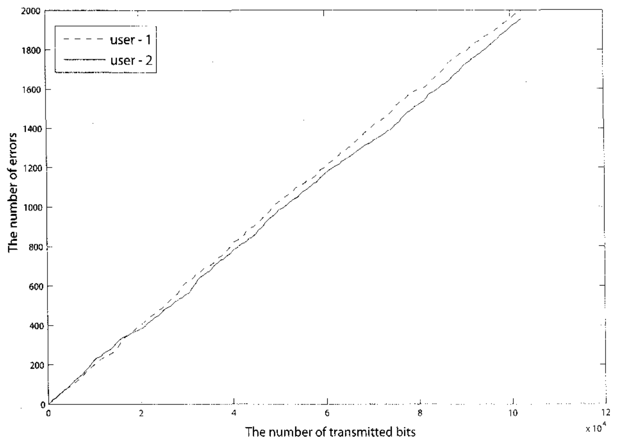

Fig. 4. Two user, self-encoded multiple access, 64 chips/bit, with user mask, AWGN.

efficiently. In practice, the user mask can be generated using a user handset electronic serial number (ESN) and mobile identification number (MIN) in cellular systems [6]. For example, the mobile generates a private long code mask based on the mobile handset ESN. The private long code mask is utilized in both mobile and the networks to change the characteristics of a long code. This modified long code is used for voice scrambling, which adds an extra level of privacy over the air interface in cellular standards such as IS-95 [7], cdma2000 [8], and WCDMA [9]. In the simulation, we have applied the private long code to the user mask for a user signal separation in our proposed system.

Fig. 3 shows the effect of multiuser crosstalk without the user mask. The statistical nature of the users random data is such that after some initial transmission period, the number of errors for user-2 would increase abruptly compared to user-1. This means that the multiuser crosstalk in fact has caused user-2 receiver to track the transmission of user-1. Fig. 4 shows that the crosstalk has been eliminated after the user masks were applied to each users' self-encoded spreading sequences. This demonstrates that the user mask scheme is necessary to maintain a reliable communication performance in a self-encoded multiple access environment. Another issue associated with SEMA systems is that iterative detection may be infeasible due to multiple access interference that increases the error probability, thereby rendering the iteration chips unreliable. We employ an interference cancellation scheme [10]–[12] to reduce the multiple access interference at the receiver.

As shown in Fig. 1 for the receiver, after chip de-interleaving the interference signal is despread and the interfering bits are detected. The interfering signals are then reconstructed from detected interfering bits and subtracted from the received signal in order to cancel the multiuser interference. This cancellation scheme is not blind as it requires the knowledge of other users' spreading sequences. However, it has the advantage of exhibiting a computational complexity that is linear with respect to the number of users.

## IV. NUMERICAL RESULT

The performance of the proposed system in fading channels has been verified with the following simulation results. The simulation assumed flat fading that is constant over one bit and is independent from bit to bit ([5], p. 817), ([13], p. 543), [14], [15]. Fig. 5 shows the single-user BER under such Rayleigh fading. The plots compare the performance between chip-interleaving only, iterative detection only, and chip-interleaving with iterative detection. The result clearly shows the diversity gain: The performance of chip-interleaving and iterative detection is significantly better than BPSK system under flat fading. The simulation result agrees well with the analytical result under high SNR ($\geq$ 5 dB). The difference of the analytical result at low SNR is primarily due to the fact that self-interference, caused by detection errors which are more serious at low SNR, was not included for the convenience of analysis. Notice that the proposed scheme achieves a 3 dB gain over chip-interleaving only and iterative detection only. In fact, this expected 3 dB gain performance is also better than BPSK in AWGN only channels. Fig. 6

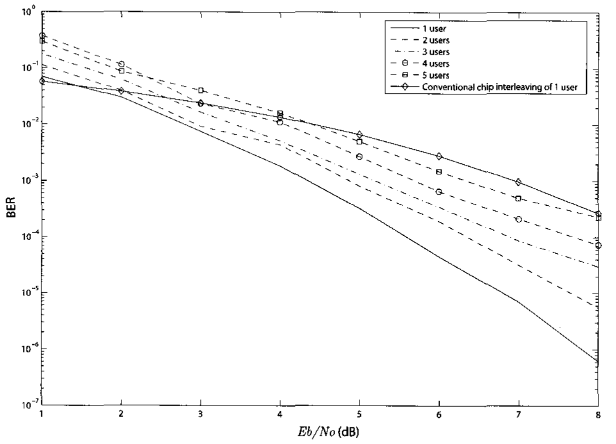

Fig. 6. Simulation BER, chip interleaved iterative detection, interference cancellation, 2, 3, 4, 5 users, 64 chips/bit, Rayleigh fading.

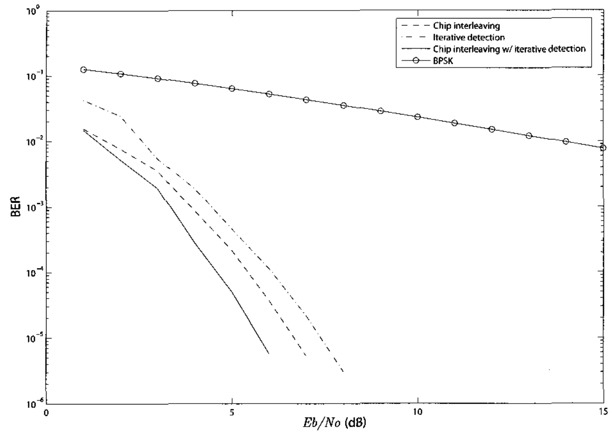

Fig. 8. Simulation BER, Rake receiver, 64 chips/bit, single user, multipath channels.

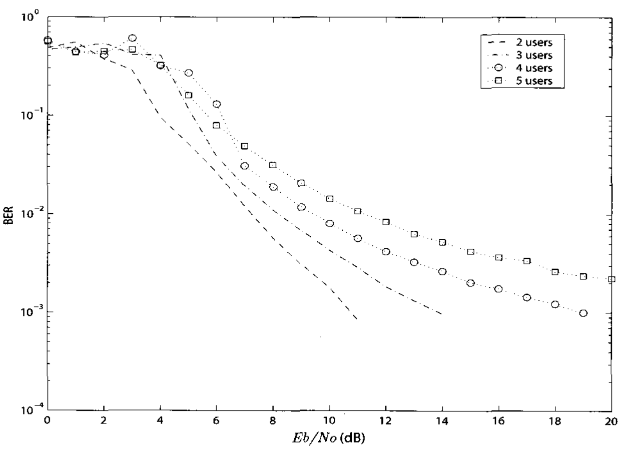

Fig. 7. Simulation BER, iterative detection without chip-interleaving, interference cancellation, 2, 3, 4, 5 users, 64 chips/bit, Rayleigh fading.

shows the performance of the proposed system in a multiple access environment. As the number of users increases, we can still observe moderately good performance. For $E_b/N_o \geq 5$ dB, the performance under 4 users with chip-interleaving and iterative detection is better than single user with chip-interleaving only. Although the iterative detection degrades gradually with the number of users due to the increased multiuser interference, there is still significant performance improvement over the chip-interleaving only system. The BER without the chip-interleaving can be compared in Fig. 7 for the same simulation parameters. For example, with 2 and 4 users, Fig. 6 shows that the BER is better than $10^{-4}$ and $10^{-5}$ at SNR $= 8$ dB, respectively. The corresponding BER in Fig. 7 is approximately $2\times10^{-2}$ and $6\times10^{-3}$, respectively. Notice also that the interference cancellation scheme without the chip-interleaving (Fig. 7) does not work as well at low SNR due to the presence of self interference. We can observe, from Fig. 6, a significant improvement in this respect with chip-interleaving. The single-user performance in multipath fading channels with a Rake receiver is shown in Fig. 8 that compares the BER of the chip-interleaving only, iterative detection only, and the proposed system. The simulation assumed a two-path model with a half-bit time delay and a half-amplitude attenuation of the second path with respect to the direct path. The plots demonstrate that BER performance of the proposed system is also superior to both chip-interleaving only and iterative detection only systems in multipath fading channels, especially under large SNRs.

## V. CONCLUSION

In this paper, we have proposed a chip interleaving and iterative detection scheme for self-encoded multiple-access communications. The proposed system exploits the inherent diversity in self-encoded spreading sequences. This has been shown not only to improve the received signal strength but also to maintain a robust performance under the presence of signal fluctuation and attenuation in a wireless mobile communication environment. The result has demonstrated that the proposed system can achieve a 3 dB power gain and possess a diversity gain that can yield significant performance improvement in both Rayleigh and multipath fading channels.

## ACKNOWLEDGMENTS

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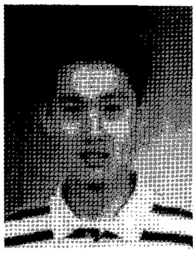

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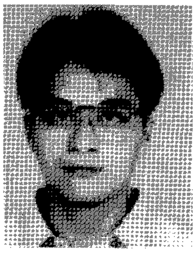

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