Optical CDMA Using Dual Encoding with Different Optical Power

Shusaku Hata, Hiroyuki Yashima
Department of Management Science, Faculty of Engineering
Tokyo University of Science
1-3, Kagurazaka, Shinjuku-ku, Tokyo, Japan
E-mail: hatah@ms.kagu.tus.ac.jp, yashima@ms.kagu.tus.ac.jp

***Abstract*— In this paper, we propose optical code division multiple access (CDMA) systems using dual encoding with different optical power to improve system performance. In the proposed system, each user has two signature sequences, and an information bit is modulated by the sequences with the different power. In the receiver, the received signal is fed into optical hard limiter (OHL). The reflected signal and the transmitted signal of OHL are decoded by corresponding decoders of the sequences, respectively. At each decoder, correlation between received sequence and an assigned sequence is calculated and then information bit is detected. We theoretically derive bit error rate (BER), and show that our proposed system can significantly improve BER.**

Keywords-optical code division multiple access(CDMA); power control; optical orthogonal codes.

I. INTRODUCTION

Recently, Optical Code Division Multiple Access (CDMA) systems attract much attention particularly in the field of fiber optic networks. In optical CDMA systems, each user is assigned a unique signature sequence to allow multiple accesses. Information bit is modulated by On-Off Keying (OOK) signaling, then coded by each encoder, which has own signature sequence [1]-[13]. Signals of all users are coupled and send to optical fiber network. At the receiver, multiplexed signal is fed into a decoder and correlated with its sequence. When the correlation value is larger than decision threshold, received bit is determined as “1”, otherwise as “0.” Generally, optical CDMA systems suffer from multiple access interferences (MAI) from other simultaneous users. In order to decrease MAI, signature sequences are constructed so that cross correlation is small. Optical Orthogonal Code (OOC) with $\lambda_a = \lambda_c = 1$ is frequently used, and is discussed on its construction methods and its property [1]-[5]. Here, λ_a is the maximum off-peak of auto correlation, and λ_c is the maximum cross correlation. The code length must be long to improve the BER, but it reduces bit rate. Increasing weight of sequence also improve the BER, however, the available number of user decrease. Since OOC with $\lambda_c = 1$ is restricted in the number of sequence for a given code length, OOC with $\lambda_c \geq 1$ is also discussed to increase the number of sequence [6].

In order to improve the BER, various methods have been reported [7]-[9]. In [1], an optical hard limiter (OHL), where nonlinear optical effect is used for limiting power of optical signal, is placed at the front of the receiver to reduce the effect of interference.

On the other hand, optical CDMA systems using different optical power have been also proposed [10]-[12]. In [11], users are divided into some groups, and each user uses the optical power level assigned to own group, then users of different groups can obtain different BER. In conventional researches, different optical power is used to achieve different requirement on BER in multimedia communications or increase the number of user.

In this paper, we propose an optical CDMA using dual encoding with different optical power to improve BER by using two levels of optical power by each user. In the proposed system, each user has two signature sequences, and an information bit is modulated by the two sequences with different power levels. In the receiver, the received signal is passed through OHL, and the reflected signal and the transmitted signal of OHL are decoded by corresponding decoders, respectively. The proposed transmitter and receiver can remove MAI between signals of different power. Since we can increase the weight of sequence without increasing MAI in the same code length, the BER is improved. Moreover, we discuss how to assign two sequences to each user. By using cyclic shifted sequence, we can assign sequences without decreasing the number of user. We also derive BER theoretically, and show the proposed system provides significant performance improvement.

II. SYSTEM DESCRIPTION

Fig. 1 shows a block diagram of the transmitter of the proposed system. There are N simultaneous users and each have two encoders that are assigned different sequences. We use OOC, whose code length and number of weights are F and k, respectively. Here, the two sequences of user i is denoted by $C_{i,1}$ and $C_{i,2}$, respectively. An information bit is coded by both encoder 1 with $C_{i,1}$ and encoder 2 with $C_{i,2}$. The output of the encoder 1 and encoder 2 are modulated by optical power P and 2P, respectively.

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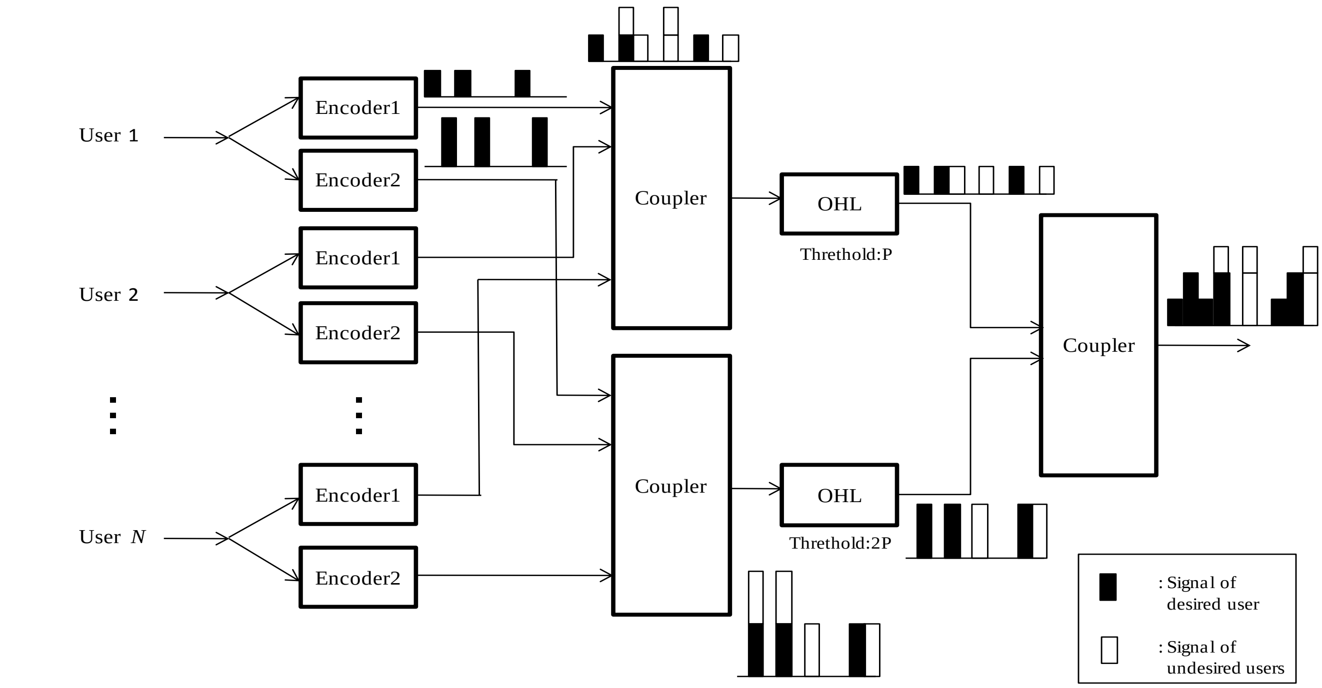

Figure 1. Block diagram of the transmitter of the proposed system.

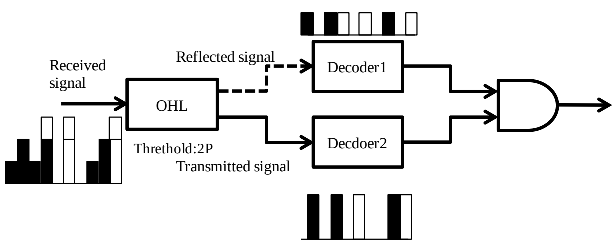

Figure 2. Block diagram of the receiver of the proposed system.

TABLE 1. Input and output characteristics of the OHL

Received signal	Transmitted signal	Reflected signal
0	0	0
P	0	P
2P	2P	0
3P	2P	P

Signals of the same power from all transmitters are once coupled at the coupler, and are fed into OHLs with threshold P and 2P only to transmit the minimum optical signal to reduce interference. The output signal power I_{tr} of the OHL for input x is given by [13]

$$I_{tr}(x) = \begin{cases} th, & x \geq th \\ 0, & 0 \leq x < th \end{cases}, \qquad (1)$$

where th is the output threshold of the OHL, and given by P and 2P, respectively. The outputs of two OHLs are coupled by the coupler and the output of the coupler is sent to optical fiber networks. The output of the coupler consists of signals of power P, 2P and 3P, which are single sum of power P and 2P.

Fig. 2 shows a block diagram of the receiver of the proposed system. The received signal is fed into OHL with threshold 2P. The output of OHL consists of reflected signal and transmitted signal. TABLE 1 shows intensity of transmitted signal and reflected signal for the received signal. Thus, encoded signals by the encoder 1 and 2 appear at the output as the transmitted signal and the reflected signal at the output of OHL, respectively. Decoder 1 with the sequence $C_{i,1}$ decodes the sequence coded by encoder 1 modulated with P, and also, decoder 2 with the signature $C_{i,2}$ decodes the sequence coded by encoder 2 modulated with 2P. Namely, two signals modulated by the different power do not interfere with each other. At the each decoder, when the correlation with the corresponding sequence is larger than the threshold k, which is the weight of the sequence, the output of decoders is "1". In the case of both outputs of two decoders are "1", received bit is determined as "1", otherwise as "0".

III. CODE CONSTRUCTION

In this section, we explain construction method of the sequence. $C_{i,1}$ is OOC with $\lambda_a = \lambda_c = 1$ generated by Greedy algorithm [4]. $C_{i,2}$ is given by cyclic shift of $C_{i,1}$ by Si. Then, the element of the sequence is $C_{i,2}(n) = C_{i,1}(n \oplus S_i)$, $(0 < n < F\text{-}1)$, where $C_{i,1}(n)$ denotes nth bit of the sequence of 0 or 1 and "$\oplus$" denotes modulo-F addition. $C_{i,1}$ and $C_{i,2}$ are used in the same users and transmitted synchronously, so we can use cyclic shifted

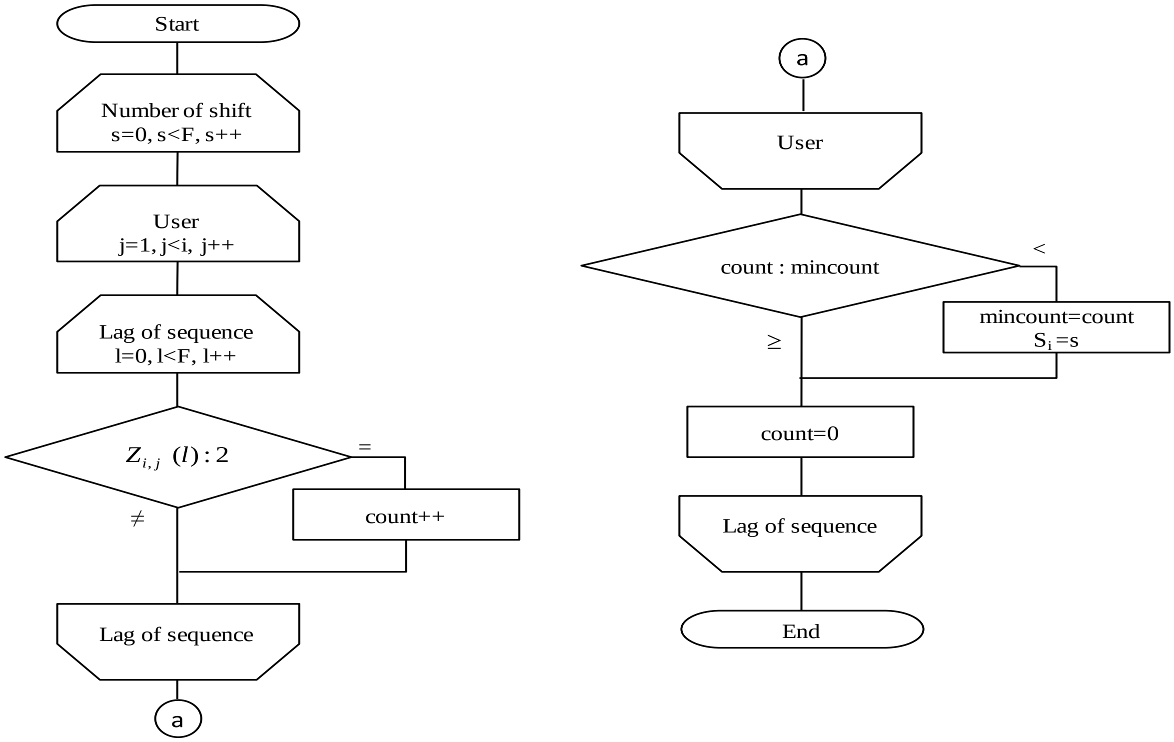

Figure 3. The algorithm of determining *Si*.

TABLE 2. Number of sequence

N, k, F	20, 3, 127	30, 4, 464	50, 4, 777	50, 5, 1514
Number of sequecne	10	11	22	21

TABLE 3. Event probability of frequency of cross correlation

N, k, F	20, 3, 127	30, 4, 464	50, 4, 777	50, 5, 1514
$Z_{i,j}(l) = 0$	20741	187969	912688	1793494
$Z_{i,j}(l) = 1$	3389	13871	39137	61156
$Z_{i,j}(l) = 2$	31	49	63	94

sequence code of $C_{i,1}$ as $C_{i,2}$. Thus, although the proposed system requires two sequence codes for each user, we can assign sequence codes without decreasing the number of users. Since there are no interferences between signals of different power, maximum value of cross correlation between sequences of same power is 1. However, we should consider the case that $C_{i,1}$ and $C_{i,2}$ are interfered simultaneously from one user. Thus, we define cross correlation between sequences of user $C_{i,1}$ and $C_{i,2}$ to determine S_i. Considering that $C_{i,1}$ and $C_{i,2}$ are used synchronously, the cross correlation can be expressed as

$$Z_{i,j}(l) = \sum_{n=0}^{F-1}\{C_{i,1}(n)\cdot C_{j,1}(n\oplus l) + C_{i,2}(n)\cdot C_{j,2}(n\oplus l)\} \quad for \quad 0 \le l < F. \tag{2}$$

Note that the maximum value of $Z_{i,j}(l)$ is two, when the correlations of both code coincidently take value one, and in this case the influence of MAI increases. For reducing interferences of undesired users, S_i is given so as to satisfy $Z_{i,j}(l) < 1$ for all *l*. We show an algorithm of determining S_i in Fig. 3.

We determine S_i using the algorithm shown in Fig. 3, then the number of sequence satisfying $Z_{i,j}(l) \le 1$ is shown in TABLE 2. To accommodate more users, we can also use the sequences with S_i so that the total number of *l* being $Z_{i,j}(l) = 2$ is as small as possible. TABLE 3 shows frequency of $Z_{i,j}(l) =$ 0, 1 and 2 for all combinations of *l* and pairs of *i* and *j*. It is found that the influence of $Z_{i,j}(l) = 2$ is small, because the event probability of $Z_{i,j}(l) = 2$ in the all combinations is very few. In OOC with F = 127, k = 3, N = 20, the event probability of $Z_{i,j}(l) = 2$ in the all combinations is only 1.3×10^{-3}.

IV. PERFORMANCE ANALYSIS

In this section, we derive the BER of the proposed system. To investigate the basic performance of the proposed system, we do not consider any noise in this analysis and we only consider MAI to corrupt signal. We assume that only sequences satisfying $Z_{i,j}(l) \le 1$ are used. A bit error occurs when desired user sends "0" and both of correlation values of two decoders exceed a decision threshold simultaneously. The probability q that a pulse from an undesired user overlaps with a pulse of the desired user is given by

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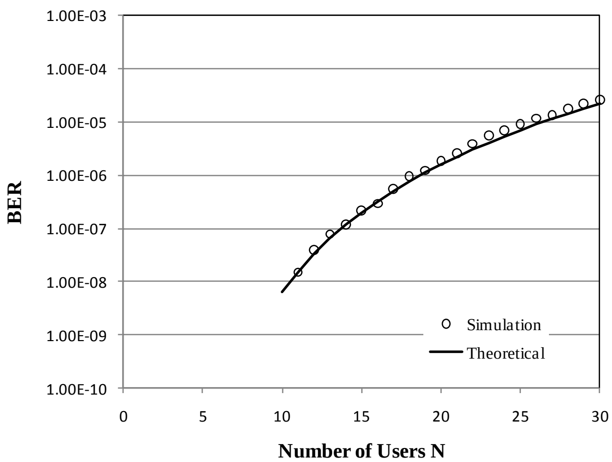

Figure 4. BER versus the number of users N for theoretical and simulation (F=464, k=4).

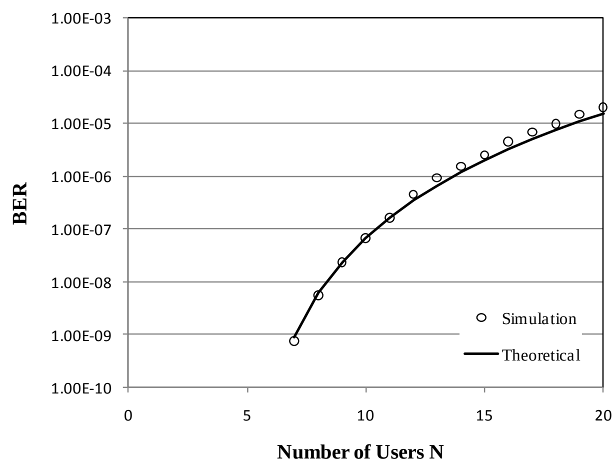

Figure 5. BER versus the number of users N for theoretical and simulation (F=127, k=3).

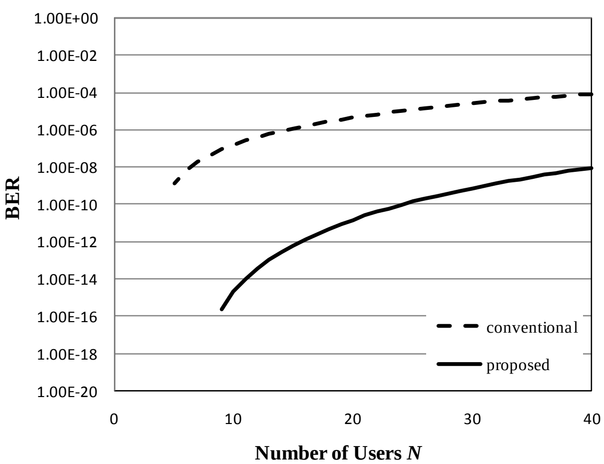

Figure 6. BER versus the number of users N for conventional optical CDMA and our proposed system (F=620, k=4).

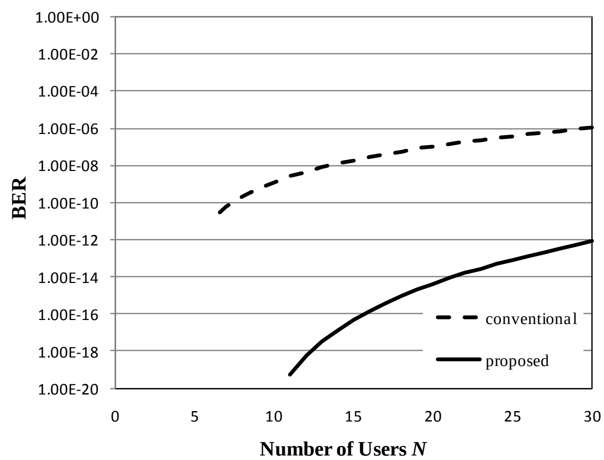

Figure 7. BER versus the number of users N for conventional optical CDMA and our proposed system (F=890, k=5).

$$q = 1 - \frac{k}{2F}. \tag{3}$$

The probability that at least one undesired user overlaps the pulse is given by $1-q^{N-1}$. Since total number of chips is $2k$, the BER, *Pe*, can be expressed as

$$Pe \le \frac{1}{2}\prod_{m=0}^{2k-1}(1-q^{N-1-m}). \tag{4}$$

V. NUMERICAL RESULTS

Figs. 4 and 5 show the BER given by (4), and simulation. We use OOC with F = 464, k = 4 in Fig. 4, and OOC with F = 127, k = 3 in Fig. 5. In both figures, when N is smaller than number of sequence in TABLE 2, simulation value is almost equal with theoretical value. The BER is slightly degraded when N is large, because (4) is on the assumption that all sequence is satisfy $Z_{i,j}(l) \le 1$. Although combinations of sequences to be $Z_{i,j}(l) = 2$ slightly exist, the probability of $Z_{i,j}(l) = 2$ is very small as in TABLE 3, and the degradation can be ignored.

Fig. 6 shows the BER of the proposed system given by (4) versus the number of users N for F = 620, k = 4 together with conventional system. As the conventional system, we assume the optical CDMA system using OOC having the same parameter and placing OHL in front of receivers [5]. In order to keep BER less than 10^{-8}, the conventional system can accommodate only 5 users, but our proposed system can accommodate 40 users.

Fig. 7 shows BER versus the number of users for proposed system for F = 890, k=5 together with conventional system. In case of N=30, BER of conventional system is 10^{-6}, while BER of the proposed system achieves 10^{-12}.

VI. CONCLUSION

In this paper, we have proposed a new optical CDMA using dual encoding with different optical powers in order

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to improve system performance. Each user has two signature sequences, and an information bit is modulated by these sequences with different power levels. By using the proposed transmitter and receiver, there are no interferences between signals of different power. We show construction method of sequence so that the maximum value of cross correlation is small. We also derive BER theoretically. As a result, it is shown that our proposed systems significantly improve the performance of optical CDMA systems.

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