Channel Interference Reduction Using Random Manchester Codes for Both Synchronous and Asynchronous Fiber-Optic CDMA Systems

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***Abstract*—In this paper, we propose the random Manchester codes (RMC) to improve the bit error probability (BEP) performance in both synchronous and asynchronous fiber-optic code-division multiple-access (CDMA) systems. The spreading sequences used in the synchronous and asynchronous systems are modified prime sequence codes and optical orthogonal codes (OOC's), respectively. Thermal noise, shot noise, and avalanche photodiode (APD) bulk and surface leakage currents are taken into consideration in the BEP analyzes. The results show that the proposed systems can support a larger number of simultaneous users than other systems with similar system complexity under the same bit-error probability constraint.**

***Index Terms*—Code division multiple access (CDMA), optical fiber communication, optical hardlimiter, optical orthogonal codes, prime sequence codes.**

I. Introduction

CODE division multiple access (CDMA) has been applied in fiber-optic communications and reported in the literature [1]–[11]. The CDMA fiber-optic communication system can provide a multiple access environment without using wavelength sensitive components, which are needed in the wavelength division multiple access network, and without employing very high-speed electronic data processing devices, which are necessary in the time division multiple access network. The extremely wide transmission bandwidth of single mode optical fibers is inherently suitable for this spread spectrum multiple access technique. Depending on the requirement of time synchronization, there are synchronous or asynchronous fiber-optic CDMA systems. Synchronous systems, which are more complex because they need network-wide time synchronization, can accommodate much more users than asynchronous systems conditional on using the spreading sequence with same length.

The commonly used spreading sequences in synchronous and asynchronous fiber-optic CDMA systems are modified prime sequence codes [5], [6] and optical orthogonal codes (OOC's) [1], [2], [16], respectively. The modified prime sequence codes are used in the synchronous systems because they can afford many more codes than OOC's. OOC's, however, have better autocorrelation and cross correlation properties than the modified prime sequence codes so that they are suitable in the asynchronous systems. Because the fiber-optic CDMA systems are interference limited systems, the number of simultaneous users is much less than the number of the subscribers. Several schemes have been proposed to improve the system performance. For example, error control coding can be used to reduced the BEP [12]–[14]. The receiver with double hardlimiters has been recommended to improve the system performance for both synchronous and asynchronous fiber-optic CDMA systems [3], [4]. Multi-attribute coding has been introduced to make the systems more bandwidth and broadcast efficient [9], [10], [17].

In this paper, we propose the random Manchester codes (RMC) scheme which can improve the bit error probability (BEP) performance in both synchronous and asynchronous fiber-optic CDMA systems. Compared with the double optical hardlimiters system, the employment of the RMC scheme increases the system complexity little, but improves the performance significantly. In the BEP analyses, thermal noise, shot noise, and avalanche photodiode (APD) bulk and surface leakage currents are taken into consideration. The results show that this system can support a larger number of simultaneous users than other systems with similar system complexity under the same BEP constraint. In other words, under the same number of simultaneous users, the BEP is smaller.

The remainder of this paper is organized as follows. In Section II, we describe the RMC scheme and the system architecture. The BEP analyzes for both synchronous and asynchronous systems are given in Section III. Section IV presents the numerical results and comparisons with other systems. Some discussions are also given in this section. Finally, Section V concludes this paper.

II. System Description

The Manchester encoding is often used in the baseband signal transmissions to simplify the synchronization of the receiver with the transmitter among other advantages [18]. There are several ways to implement Manchester codes. For example, the binary "1" can be represented by a pulse in the first half interval of the bit followed by absence of pulse in the second half interval. For binary "0," the locations of presence and absence of the pulse are reversed. In the conventional fiber-optic CDMA systems, the arrangement of the optical pulses and chip times of a spreading sequence are shown in Fig. 1(a) or (b) [1], [2]. In

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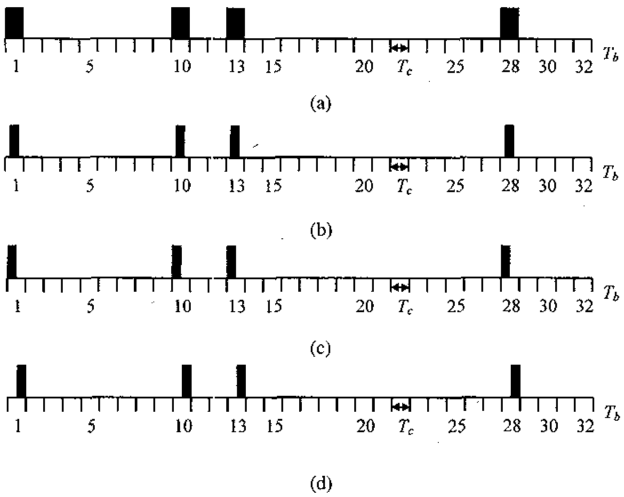

Fig. 1. (a), (b) Arrangement of optical pulses and chip times of a spreading sequence for conventional schemes and (c), (d) the arrangement of optical pulses and chip times of a spreading sequence for the RMC scheme.

these cases, the optical pulses are at the fixed positions with respect to the chip time. In this paper, we apply the RMC scheme, in which the optical pulses are sent randomly in the first half interval of the chip time or the second half interval of the chip time, in the spreading sequences. For example, the transmitter can transmit data bit "1" by sending the patterns of optical pulses either one as shown in Fig. 1(c) and (d) randomly, i.e., place the pulses in the first half chip intervals or the second half chip intervals for one spreading sequence. The data bit "0" is represented by absence of optical pulses. Then the total photon arrival rate at the input of the first optical hardlimiter, $s(t)$, is

$$s(t) = \sum_{k=1}^{N} d^k(t) \tag{5}$$

The receiver structure is the same as the conventional fiber-optic CDMA receiver with double optical hardlimiters as shown in Fig. 2 [3], [4]. The first optical hardlimiter placed before the optical correlator cuts down the interference higher than the possible level, and then the second optical hardlimiter further reduces the interference which is too small to be the desired signal. The two optical hardlimiters, however, cannot eliminate interferences completely. So the bit error is mainly due to the remained interferences. Using the RMC scheme in the transmitter can improve the BEP performance in this double optical hardlimiter CDMA receiver. If all the transmitters choose the same half interval of the chip time to transmit "1," the BEP performance is the same as that without the RMC scheme. But when the transmitters randomly select the transmission intervals, which is the usual case, the optical hardlimiter placed after the optical correlator reduces interference much more effectively. An example is given in Fig. 3. Fig. 3(a) and (b) are the correlation pattern for the optical correlator in the receiver for desired data bits "1" and "0," respectively. For the conventional double hardlimiter system without using the RMC scheme, if the desired received bit is "0," and five other users send data

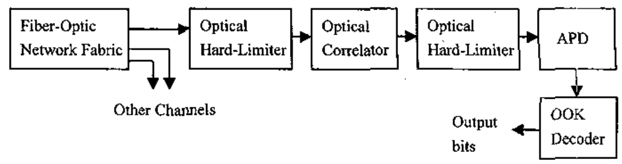

Fig. 2. Block diagram of a fiber-optic CDMA receiver with double optical hardlimiters.

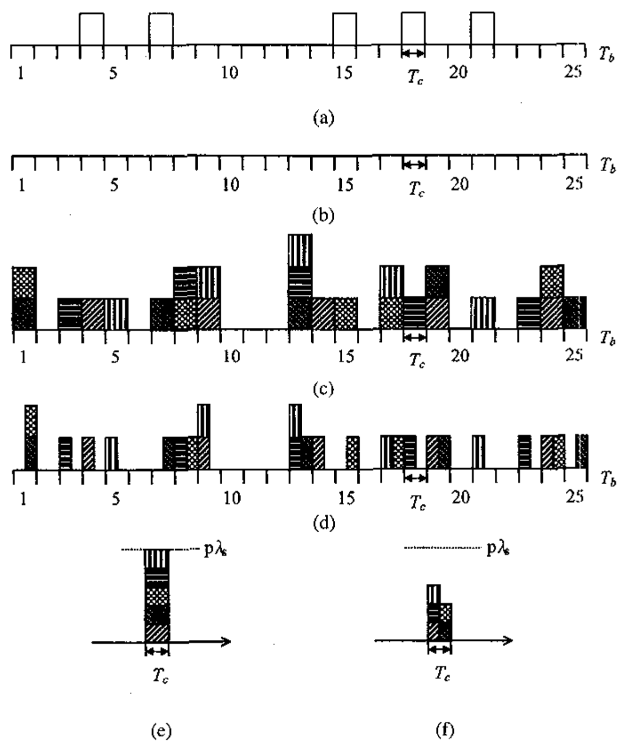

Fig. 3. (a), (b) Correlation patterns for the optical correlator in the receiver for desired data bits "1" and "0," respectively, (c) an example of the received bit pattern without the RMC scheme when the desired received data bit is "0," (d) an example of the received bit pattern with the RMC scheme when the desired received data bit is "0," and (e), (f) the optical pulses after the optical correlator in the last chip time for (c) and (d), respectively, where $p\lambda_s$ is the threshold of the optical hardlimiters.

bit "1" as shown in Fig. 3(c), the optical pulse after the optical correlator at the last chip time is like that shown in Fig. 3(e). Therefore, the received bit will by mistaken as "1." If the RMC scheme is applied to all the transmitters, the received bit pattern is probably like the one shown in Fig. 3(d). The optical pulse after the optical correlator at the last chip time is shown in Fig. 3(f). The second hardlimiter can remove the interference completely and the decoding result is correct.

III. System Performances

A. Performance of Synchronous Fiber-Optic CDMA System with RMC

In the synchronous fiber-optic CDMA system, the modified prime sequence codes are employed as the spreading sequences. It is assumed that each user is assigned a unique modified prime sequence code of length p^2. For example, the spreading sequence of the kth user is $(a_0^k, a_1^k, \ldots, a_{p^2-1}^k)$, where $a_i^k \in \{0, 1\}$ and the periodic spreading waveform can be written as

$$a^k(t) = \sum_{i=-\infty}^{\infty} a_i^k P_{T_c}(t - iT_c) \tag{1}$$

where

$a_{i+p^2}^k = a_i^k$ for all integers i;

$P_{T_c}(\cdot)$ unit-amplitude rectangular pulse of one chip time duration, T_c;

defined by

$$P_{T_c}(t) = \begin{cases} 1, & 0 < t < T_c \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

At the input of first optical hardlimiter, the photon arrival rate of the kth user can be expressed as

$$d^k(t) = \sum_{j=-\infty}^{\infty} p\lambda_s b_j^k P_{T_b}(t - jT_b) a^k(t) \cdot \sum_{l=-\infty}^{\infty} P_{T_c/2}(t - S_j^k \cdot T_c/2 - lT_c) \tag{3}$$

where

$p\lambda_s$ photon arrival rate of the chip;

$b_j^k \in \{0, 1\}$ data bit;

$T_b = p^2 T_c$ bit duration;

$P_{T_b}(\cdot)$ unit-amplitude rectangular pulses of duration T_b;

$P_{T_c/2}(\cdot)$ unit-amplitude rectangular pulses of duration $T_c/2$.

The last term in the above equation represents the effect of RMC, where S_j^k is a discrete random variable whose distribution is as follows:

$$\Pr\{S_j^k = 0\} = \Pr\{S_j^k = 1\} = 1/2. \tag{4}$$

where N is the number of simultaneous users.

The two optical hardlimiters used in the receiver can be expressed as

$$g(x) = \begin{cases} p\lambda_s, & x \geq p\lambda_s \\ 0, & 0 \leq x < p\lambda_s \end{cases} \tag{6}$$

where

x input photon rate;

$g(x)$ output photon rate.

For modified prime sequence codes and a given prime number p, the length of the spreading sequences is p^2. There are p groups and each group contains p spreading sequences, where the code sequences which are time-shifted versions of one another belong to the same group. Without loss of generality, the first user is destined as the desired user. We express the number of simultaneous users which have a mark at the same position as the ith mark of the first user as T_i: $i \in \{1, 2, \ldots, p\}$ and $T_i \in \{0, 1, \ldots, p-1\}$. Denoting the vectors $(T_1, T_2, \ldots, T_p)$ and $(t_1, t_2, \ldots, t_p)$ by $\boldsymbol{T}$ and $\boldsymbol{t}$, respectively, the probability density function of $\boldsymbol{T}$ at $\boldsymbol{t}$ is derived as

$$\Pr\{\boldsymbol{T} = \boldsymbol{t}\} = \frac{\binom{p-1}{t_1}\binom{p-1}{t_2}\cdots\binom{p-1}{t_p}\binom{p-1}{\varphi}}{\binom{p^2-1}{N-1}} \tag{7}$$

where

$$\varphi = N - 1 - \sum_{i=1}^{p} t_i \tag{8}$$

$$t_i \in \{t_{i,\min}, t_{i,\min}+1, \ldots, t_{i,\max}\} \tag{9}$$

$$t_{i,\min} = \max\left\{0, N - p - (p-i)(p-1) - \sum_{j=1}^{i-1} t_j\right\} \tag{10}$$

$$t_{i,\max} = \min\left\{N - 1 - \sum_{j=1}^{i-1} t_j, p-1\right\} \tag{11}$$

and the functions $\max\{x, y\}$ and $\min\{x, y\}$ are the maximum and minimum of x and y, respectively.

The number of users sending data bit "1" among t_i users is denoted as κ_i: $\kappa_i \in \{0, 1, \ldots, t_i\}$. Let

$$\boldsymbol{\kappa} \equiv (\kappa_1, \kappa_2, \ldots, \kappa_p) \tag{12}$$

be the interference state pattern. Furthermore, we denote the number of users sending optical pulses in the first half interval of the chip time among κ_i users as κ_i': $\kappa_i' \in \{0, 1, \ldots, \kappa_i\}$. Also let

$$\boldsymbol{\kappa}' \equiv (\kappa_1', \kappa_2', \ldots, \kappa_p') \tag{13}$$

and $|\boldsymbol{\kappa}'|$ be the number of nonzero elements in $\boldsymbol{\kappa}'$. To simplify the notation of the following calculation, we denote $\boldsymbol{\kappa}'' = \boldsymbol{\kappa} - \boldsymbol{\kappa}'$. Under the assumption that $\Pr\{b_j^k = 0\} = \Pr\{b_j^k = 1\} = 1/2$, the conditional probability density function of κ_i is given as

$$\Pr\{\kappa_i = l_i | T_i = t_i\} = \binom{t_i}{l_i} \cdot 2^{-t_i}. \tag{14}$$

And from the distribution of s_j^k, we can have $\Pr\{\kappa_i' = l_i' | \kappa_i = l_i\}$ as

$$\Pr\{\kappa_i' = l_i' | \kappa_i = l_i\} = \binom{l_i}{l_i'} \cdot 2^{-l_i}. \tag{15}$$

The accumulated APD output of the first user over the last chip time is denoted as Y and its conditional probability density function is as follows:

$$P_Y\left(y | b_j^1 = 1, |\boldsymbol{\kappa}'| = n_1, |\boldsymbol{\kappa}''| = n_2\right) = \frac{1}{\sqrt{2\pi\sigma_{y,1}^2}} e^{-(y-\mu_{y,1})^2/2\sigma_{y,1}^2} \tag{16}$$

where the mean $\mu_{y,1}$ can be expressed as

$$\mu_{y,1} = GT_c[m_1\lambda_s + I_b/e] + T_cI_s/e \tag{17}$$

where
- G average APD gain;
- e electron charge;
- I_b/e contribution of the APD bulk leakage current to the APD output;
- I_s APD surface leakage current;
- m_1 contribution of the desired signal and the multiple access interference (MAI);

$$m_1 = \begin{cases} p, & \text{if } S_1^j = 0 \cap n_2 = p \\ & \quad \text{or } S_1^j = 1 \cap n_1 = p \\ p/2, & \text{otherwise} \end{cases} \tag{18}$$

and the variance $\sigma_{y,1}^2$ can be expressed as

$$\sigma_{y,1}^2 = G^2F_eT_c[m_1\lambda_s + I_b/e] + T_cI_s/e + \sigma_{th}^2 \tag{19}$$

where F_e is the excess noise factor given by

$$F_e = k_{\text{eff}}G + (2 - 1/G)(1 - k_{\text{eff}}) \tag{20}$$

where
- k_{eff} APD effective ionization ratio;
- σ_{th}^2 variance of thermal noise expressed as

$$\sigma_{th}^2 = 2k_BT_rT_c/(e^2R_L) \tag{21}$$

where
- k_B Boltzmann's constant;
- T_r receiver noise temperature;
- R_L receiver load resistance.

$$P_Y\left(y|b_j^1 = 0, |\boldsymbol{\kappa}'| = n_1, |\boldsymbol{\kappa}''| = n_2\right) = \frac{1}{\sqrt{2\pi\sigma_{y,0}^2}}\, e^{-(y-\mu_{y,0})^2/2\sigma_{y,0}^2} \tag{22}$$

where the mean $\mu_{y,0}$ can be expressed as

$$\mu_{y,0} = GT_c[m_0\lambda_s + I_b/e] + T_cI_s/e. \tag{23}$$

m_0 is the contribution of the MAI and can be derived as

$$m_0 = \begin{cases} p, & \text{if } n_1 = p \cap n_2 = p \\ p/2, & \text{if } n_1 = p \cap n_2 < p \\ & \quad \text{or } n_1 < p \cap n_2 = p \\ 0, & \text{otherwise} \end{cases} \tag{24}$$

and the variance $\sigma_{y,0}^2$ can be expressed as

$$\sigma_{y,0}^2 = G^2F_eT_c[m_0\lambda_s + I_b/e] + T_cI_s/e + \sigma_{th}^2. \tag{25}$$

Then the BEP of the synchronous fiber-optic CDMA system with the double optical hardlimiters using the RMC scheme can be derived as

$$\begin{aligned} P_e &= \Pr\{b_j^1 = 0\} \cdot \Pr\left\{Y > \theta|b_j^1 = 0\right\} \\ &\quad + \Pr\{b_j^1 = 1\} \cdot \Pr\left\{Y < \theta|b_j^1 = 1\right\} \\ &= \frac{1}{2} \sum_{t_1=t_{1,\min}}^{t_{1,\max}} \sum_{t_2=t_{2,\min}}^{t_{2,\max}} \cdots \sum_{t_p=t_{p,\min}}^{t_{p,\max}} \sum_{l_1=0}^{t_1} \sum_{l_2=0}^{t_2} \\ &\quad \cdots \sum_{l_p=0}^{t_p} \sum_{l_1'=0}^{l_1} \sum_{l_2'=0}^{l_2} \cdots \sum_{l_p'=0}^{l_p} \\ &\quad \left[\Pr\left\{Y > \theta|b_j^1 = 0, \boldsymbol{\kappa} = \boldsymbol{l}, \boldsymbol{\kappa}' = \boldsymbol{l}'\right\}\right. \\ &\quad \left.+ \Pr\left\{Y < \theta|b_j^1 = 1, \boldsymbol{\kappa} = \boldsymbol{l}, \boldsymbol{\kappa}' = \boldsymbol{l}'\right\}\right] \\ &\quad \cdot \Pr\left\{\boldsymbol{\kappa}' = \boldsymbol{l}'|\boldsymbol{\kappa} = \boldsymbol{l}\right\} \cdot \Pr\left\{\boldsymbol{\kappa} = \boldsymbol{l}|\boldsymbol{T} = \boldsymbol{t}\right\} \\ &\quad \cdot \Pr\{\boldsymbol{T} = \boldsymbol{t}\} \end{aligned} \tag{26}$$

where

$$\Pr\left\{Y > \theta|b_j^1 = 0, \boldsymbol{\kappa} = \boldsymbol{l}, \boldsymbol{\kappa}' = \boldsymbol{l}'\right\} = \frac{1}{2}\text{erfc}\left(\frac{\theta - \mu_{y,0}}{\sqrt{2}\sigma_{y,0}}\right) \tag{27}$$

where erfc$(\cdot)$ stands for the complementary error function, defined as

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-t^2)\, dt \tag{28}$$

and

$$\begin{aligned} &\Pr\left\{Y < \theta|b_j^1 = 1, \boldsymbol{\kappa} = \boldsymbol{l}, \boldsymbol{\kappa}' = \boldsymbol{l}'\right\} \\ &\quad = 1 - \frac{1}{2}\text{erfc}\left(\frac{\theta - \mu_{y,1}}{\sqrt{2}\sigma_{y,1}}\right). \end{aligned} \tag{29}$$

The threshold level of the on–off keying (OOK) demodulator, θ, is set to a suboptimum value as [19]

$$\theta = \left.\frac{\mu_{y,0} \cdot \sigma_{y,1} + \mu_{y,1} \cdot \sigma_{y,0}}{\sigma_{y,1} + \sigma_{y,0}}\right|_{m_1=p/2,\, m_0=0}. \tag{30}$$

B. Performance of Asynchronous Fiber-Optic CDMA System with RMC

In the asynchronous fiber-optic CDMA system, we employ the OOC's with autocorrelation and cross-correlation bounded by one as the spreading sequences [1], [2], [16]. It is assumed that each user is assigned a unique code sequence of OOC's of length F and weight K. The number of available users, Φ, is bounded by

$$\Phi = \left\lfloor \frac{F-1}{K(K-1)} \right\rfloor \tag{31}$$

where the symbol $\lfloor x \rfloor$ denotes the greatest integer smaller than x. Again we destine the first user as the desired user. The spreading sequence of the kth user is $(a_0^k, a_1^k, \ldots, a_F^k)$, where $a_i^k \in \{0, 1\}$. The periodic waveform can be written in the same form as (1), where $a_{i+F}^k = a_i^k$ for all integers i. At the input of the first optical hardlimiter in the receiver, the photon arrival rate of the kth user can also be expressed as in (3) except that the photon arrival rate of the pulsed chip is $K\lambda_s$ instead of $p\lambda_s$. To calculate the upper bound of the BEP, we consider the chip synchronous case among different users [2],

[4]. Therefore, the total photon arrival rate at the input of the first optical hardlimiter, $s(t)$, is

$$s(t) = \sum_{k=1}^{N} d^k(t - M_k T_c) \tag{32}$$

where

N number of simultaneous users;

M_k discrete random variable with the following distribution function:

$$\Pr\{M_k = x\} = \begin{cases} 1/F, & \text{if } x = 0, 1, \ldots, F-1 \\ 0, & \text{otherwise.} \end{cases} \tag{33}$$

The input and output relation of the two optical hardlimiters is the same as (6) except that all $p\lambda_s$'s should be replaced by $K\lambda_s$'s.

We denote the number of hits which fall in the ith chip time of the first user from the optical pulses of the $N-1$ other users as κ_i. And define

$$\boldsymbol{\kappa} \equiv (\kappa_1, \kappa_2, \ldots, \kappa_K) \tag{34}$$

as the interference state pattern, and I is the total summation of κ_i. From [2], we have

$$\Pr\{I = i\} = \binom{N-1}{i} \left(\frac{K^2}{2F}\right)^i \left(1 - \frac{k^2}{2F}\right)^{N-1-i} \tag{35}$$

for $i = 0, 1, \ldots, N-1$. Furthermore, the number of users sending optical pulses in the first half interval of the chip time among κ_i is denoted as κ_i', and

$$\boldsymbol{\kappa}' \equiv (\kappa_1', \kappa_2', \ldots, \kappa_K') \tag{36}$$

is the state vector. Similarly, we have $\boldsymbol{\kappa}'' = \boldsymbol{\kappa} - \boldsymbol{\kappa}'$. I_1 and I_2 are the total summation of κ_i' and κ_i'', respectively. The accumulated APD output of the first user over the last chip time is also denoted as Y, and the threshold level of the OOK demodulator is θ. Then the BEP, P_e, can be expressed as

$$\begin{aligned} P_e &= \tfrac{1}{2}\left[\Pr\left\{Y > \theta | b_j^1 = 0\right\} + \Pr\left\{Y < \theta | b_j^1 = 1\right\}\right] \\ &= \tfrac{1}{2} \sum_{i=0}^{N-1} \left(\Pr\left\{Y > \theta | b_j^1 = 0, I = i\right\}\right. \\ &\quad \left. + \Pr\left\{Y < \theta | b_j^1 = 1, I = i\right\}\right) \cdot \Pr\{I = i\} \\ &= \tfrac{1}{2} \sum_{i=0}^{N-1} \sum_{i_1=0}^{i} \binom{i}{i_1} 2^{-i} \\ &\quad \cdot \left(\Pr\left\{Y > \theta | b_j^1 = 0, I_1 = i_1, I_2 = i - i_1\right\}\right. \\ &\quad \left. + \Pr\left\{Y < \theta | b_j^1 = 1, I_1 = i_1, I_2 = i - i_1\right\}\right) \\ &\quad \cdot \Pr\{I = i\} \end{aligned} \tag{37}$$

where

$$\begin{aligned} &\Pr\left\{Y < \theta | b_j^1 = 1, I_1 = i_1, I_2 = i_2\right\} \\ &= \Pr\left\{Y < \theta | b_j^1 = 1, |\boldsymbol{\kappa}'| = K, |\boldsymbol{\kappa}''| = K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| = K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| = K | I_2 = i_2\right\} \\ &\quad + \Pr\left\{Y < \theta | b_j^1 = 1, |\boldsymbol{\kappa}'| < K, |\boldsymbol{\kappa}''| = K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| < K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| = K | I_2 = i_2\right\} \\ &\quad + \Pr\left\{Y < \theta | b_j^1 = 1, |\boldsymbol{\kappa}'| = K, |\boldsymbol{\kappa}''| < K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| = K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| < K | I_2 = i_2\right\} \\ &\quad + \Pr\left\{Y < \theta | b_j^1 = 1, |\boldsymbol{\kappa}'| < K, |\boldsymbol{\kappa}''| < K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| < K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| < K | I_2 = i_2\right\} \end{aligned} \tag{38}$$

here the distribution $P_Y(y | b_j^1 = 1, |\boldsymbol{\kappa}'| = n_1, |\boldsymbol{\kappa}''| = n_2)$ is the same as that in (16). The expressions of mean and variance are also the same as those in (17) and (19). The expression of m_1 can be modified from (18) by replacing all p's to K's.

Each user is equally likely to incur interference at any one of the K mark chips independent of all other users. The interference state pattern vector, $\boldsymbol{\kappa}'$, obeys a multinomial distribution [4], [8]. Therefore,

$$\Pr\left\{|\boldsymbol{\kappa}'| = n | I_1 = i_1\right\} = \sum_{\substack{\boldsymbol{\kappa}' \in G_{I_1} \\ |\boldsymbol{\kappa}'| = n}} \mathrm{NDP}(\boldsymbol{\kappa}') P(\boldsymbol{\kappa}'; H_{I_1}) \tag{39}$$

where $n = 0, 1, \ldots, \min(K, i_1)$, and H_{I_1} is the set of all the interference pattern vectors with total weight equal to i_1, G_{I_1} is the set of representative interference vectors in H_{I_1} with elements in decreasing order, $\mathrm{NDP}(\boldsymbol{\kappa}')$ is the number of distinct permutations of the vector $\boldsymbol{\kappa}'$ in G_{I_1} and is expressed as

$$\mathrm{NDP}(\boldsymbol{\kappa}') = \frac{K!}{\prod_j R(\kappa_j)!} \tag{40}$$

where

$R(\kappa_j)!$ number of repetition times of an element κ_j in the vector $\boldsymbol{\kappa}'$ and the product is taken over j for which κ_j are distinct;

$P(\boldsymbol{\kappa}'; H_{I_1})$ multinomial distribution for the interference pattern vector $\boldsymbol{\kappa}'$ in H_{I_1};

and expressed as

$$P(\boldsymbol{\kappa}'; H_{I_1}) = \frac{i_1!}{K^{i_1} \prod_{j=1}^{K} (\kappa_j!)}. \tag{41}$$

The following relation can be utilized to simplify the calculation

$$\Pr\left\{|\boldsymbol{\kappa}'| < K | I_1 = i_1\right\} = 1 - \Pr\left\{|\boldsymbol{\kappa}'| = K | I_1 = i_1\right\}. \tag{42}$$

The distribution of $\Pr\{|\boldsymbol{\kappa}''| = n | I_2 = i_2\}$ is identical to $\Pr\{|\boldsymbol{\kappa}'| = n | I_1 = i_1\}$. Similar to (38), we have

$$\begin{aligned} &\Pr\left\{Y > \theta | b_j^1 = 0, I_1 = i_1, I_2 = i_2\right\} \\ &= \Pr\left\{Y > \theta | b_j^1 = 0, |\boldsymbol{\kappa}'| = K, |\boldsymbol{\kappa}''| = K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| = K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| = K | I_2 = i_2\right\} \\ &\quad + \Pr\left\{Y > \theta | b_j^1 = 0, |\boldsymbol{\kappa}'| < K, |\boldsymbol{\kappa}''| = K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| < K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| = K | I_2 = i_2\right\} \\ &\quad + \Pr\left\{Y > \theta | b_j^1 = 0, |\boldsymbol{\kappa}'| = K, |\boldsymbol{\kappa}''| < K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| = K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| < K | I_2 = i_2\right\} \\ &\quad + \Pr\left\{Y > \theta | b_j^1 = 0, |\boldsymbol{\kappa}'| < K, |\boldsymbol{\kappa}''| < K\right\} \\ &\quad \cdot \Pr\left\{|\boldsymbol{\kappa}'| < K | I_1 = i_1\right\} \cdot \Pr\left\{|\boldsymbol{\kappa}''| < K | I_2 = i_2\right\} \end{aligned} \tag{43}$$

TABLE I
LINK PARAMETERS

Name	Symbol	Value
Laser wavelength		825 nm
APD quantum efficiency	η	0.6
APD gain	G	100
APD effective ionization ratio	k_{eff}	0.02
APD bulk leakage current	I_b	0.1 nA
APD surface leakage current	I_s	10 nA
Data bit rate	R_b	30 Mbps
Receiver noise temperature	T_r	300 K
Receiver load resistor	R_L	1030 Ω

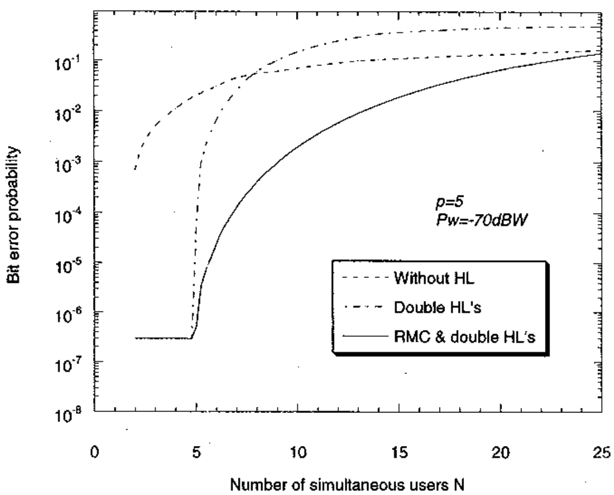

Fig. 4. BEP comparisons among three types of synchronous fiber-optic CDMA systems for $p = 5$.

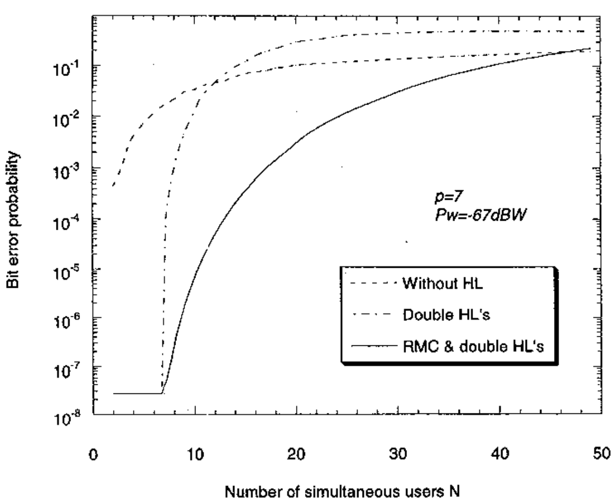

Fig. 5. BEP comparisons among three types of synchronous fiber-optic CDMA systems for $p = 7$.

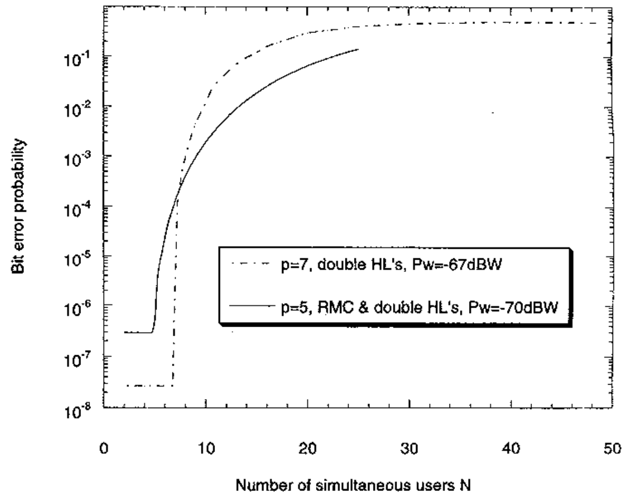

Fig. 6. BEP comparisons between two types of synchronous fiber-optic CDMA systems.

where the distribution $P_Y(y|b_j^1 = 0, |\kappa| = n_1, |\kappa'| = n_2)$ is the same as that in (22). The expressions of mean and variance are the same as those in (23) and (25). The expression of m_0 can also be obtained from (24) by replacing all p's to K's. θ is set to the suboptimum value in (30) with m_1 changing to $K/2$.

IV. Numerical Results and Discussions

We here compare the performance of three synchronous fiber-optic CDMA systems:

1) without hardlimiter;
2) with double hardlimiters;
3) with the proposed RMC scheme and double hardlimiters.

These three systems have similar complexity. The values of some common parameters are given in Table I. The numerical results are depicted in Figs. 4 and 5 for $p = 5$ and $p = 7$, respectively. The received optical power for the proposed system is defined as follows:

$$P_W = (1/2)hfp\lambda_s/\eta \tag{44}$$

where

the factor, 1/2	due to that the optical pulses are only transmitted in half of the chip time in the RMC scheme;
h	Plank's constant;
f	optical frequency;
η	APD quantum efficiency.

In fact, because fiber-optic CDMA networks are interference-limited systems, the values of P_W only affect the BEP when the number of simultaneous users, N, is smaller than or equal to p. Therefore, the following discussions only concentrate on the situations when N is larger than p. In these two figures, we can see that the BEP of the proposed scheme is much smaller that of the systems without hardlimiter or with double hardlimiters. Fig. 6 replots the two curves: double hardlimiters for $p = 7$, and the proposed scheme for $p = 5$. It is meaningful to compare these two curves because the lengths of the spreading sequences for $p = 7$ and $p = 5$ are 49 and 25, the

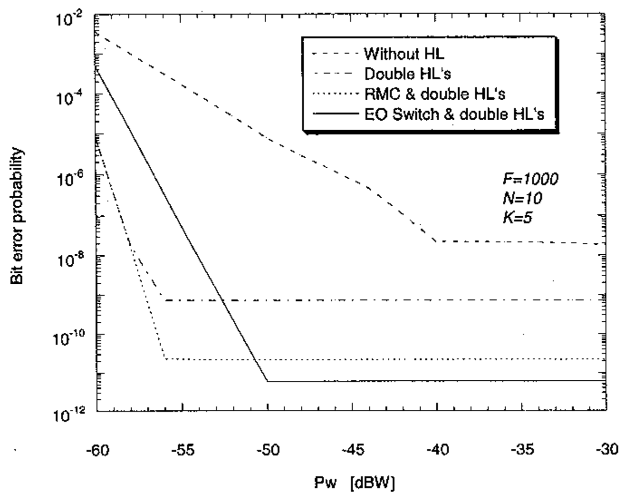

Fig. 7. BEP comparisons among four types of asynchronous fiber-optic CDMA systems for $K = 5$.

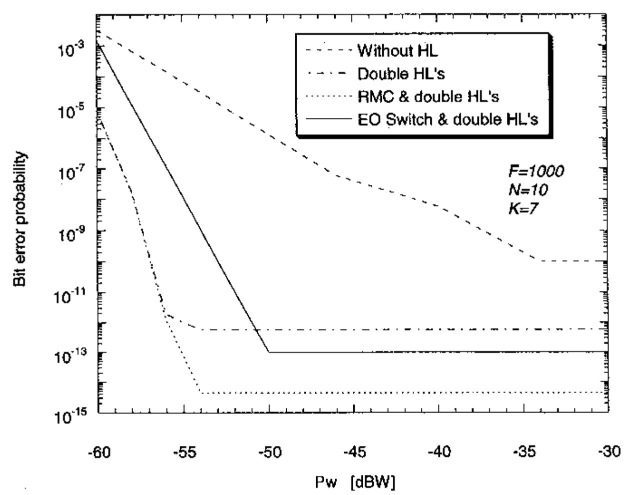

Fig. 8. BEP comparisons among four types of asynchronous fiber-optic CDMA systems for $K = 7$.

former is almost double of the latter. It is clear that the proposed scheme for $p = 5$ gets better performance. It means that even double the length of spreading sequence in the synchronous fiber-optic CDMA system with double hardlimiters can not get as small BEP as that with the RMC scheme.

Figs. 7 and 8 show the performances of four asynchronous fiber-optic CDMA systems: a) without hardlimiter, b) with double hardlimiters, c) the proposed scheme, and d) EO Switch and double hardlimiters [4]. The definition of P_W is the same as that in (44) except that p is replaced by K. These two figures give the relation of BEP versus P_W. It is seen that the proposed scheme always has better performance than that of the system without hardlimiter or with double hardlimiters. When $K = 5$, the scheme with EO switch and double hardlimiters has the best performance when P_W is large enough. When $K = 7$, however, the proposed scheme gets the best performance. The complexity of the system with EO switch and double optical hardlimiters is much higher than that of the proposed scheme. Fig. 9 gives the performance comparisons versus N. We see

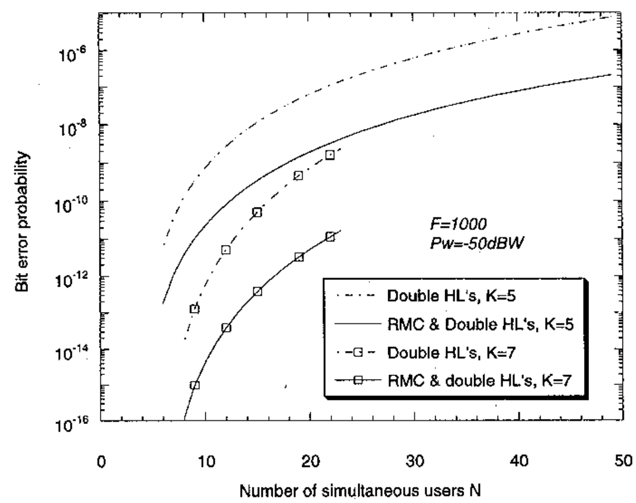

Fig. 9. BEP comparisons among asynchronous fiber-optic CDMA systems with various parameter settings.

that the employment of the RMC scheme does improve the BEP.

V. Conclusion

In this paper, we apply the RMC scheme to both synchronous and asynchronous fiber-optic CDMA systems. The spreading sequences used in the two kinds of systems are modified prime sequence codes and OOC's, respectively. To use the RMC scheme in the system, we only need to generate the optical pulses of half chip time interval and randomly assign the pulses on the first half or the second half of the chip time. Other parts of the transmitter and receiver are the same as that of the double hardlimiter system. With the very mature technology of laser mode-locking, the generation of narrow pulses is not a difficult task. Using a fiber delay line of half chip time length, the positions of the pulses can be shifted. Besides, the positions of the pulses need not to be shifted very often. They can be changed after a specified number of packets are transmitted. Therefore, incorporating the RMC scheme with the system with double hardlimiters increases the system complexity little, but improves the BEP significantly. From the numerical results, we see that under the same bit-error probability constraint, the number of simultaneous users of the proposed system is much more than that of the system without hardlimiter or with double hardlimiters in synchronous or asynchronous fiber-optic networks. In other words, under the same number of simultaneous users, the bit-error probability is much smaller.

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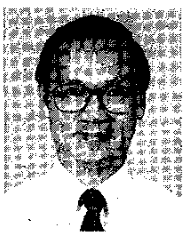

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