Optical Fiber Code-Division Multiple-Access Networks Using Concatenated Codes

Pham Manh Lam and Do Quang Minh

Abstract: **An optical fiber code-division multiple-access (CDMA) network is proposed in which encoding is based on the use of concatenated sequences of relatively large weight. The first short component sequence in the concatenated sequence permits realistic electronic encoding of each data bit. The chips of this sequence are then all-optically encoded at substantially higher rate. In spite of the relatively large weight of the sequence the all-optical encoder is practical by virtue of the shortness of the component sequences. The use of Gold and Lempel sequences as component sequences for generating the concatenated sequences is studied and the bit-error rate (BER) performance of the proposed system is presented as a function of the received optical power with the number of simultaneous users as parameter.**

Index Terms: **Optical CDMA, CDMA networks, concatenated codes.**

I. INTRODUCTION

Code-division multiple-access has been extensively studied for satellite and mobile-radio applications and more recently, for use in wireless local-area networks (LANs). As is well known, in order to accommodate a large number of users on CDMA networks, long sequences requiring large transmission bandwidths are needed, placing serious limits on radio channels and metallic transmission lines. For this reason, incoherent optical code-division multiple-access (OCDMA) over single-mode optical fibers holds out the promise of allowing the use of very long sequences. In recent years, many different schemes have been proposed for incoherent OCDMA networks. The first approach uses sequence-inversion keying (SIK) of large-weight unipolar sequences (a large number of "1s" in the sequence) and at the receiver the unipolar sequences are correlated with the bipolar form of the unipolar reference sequence [1]–[4]. Since large-weight codes can be used, the number of available sequences and hence the number of potential network subscribers is large. However, if relatively long sequences were used, the optical recombination loss rapidly becomes a serious limitation [1], [2] or the synchronous switching at the chip rate [3] is required negating a major advantage of all-optical processing. The second approach relies on low-weight codes and unipolar-unipolar correlation [5], [6]. Because the correlation is based on power summation, compared to the conventional bipolar codes of similar length these unipolar codes yield a lower ratio of the autocorrelation peak to the maximum value of the cross-correlation, and are therefore prone to higher multiple-access interference. This leads to a serious degradation in the bit error probability (BER) as the number of simultaneous users increases and the degradation can not be overcome even for arbitrary high optical power.

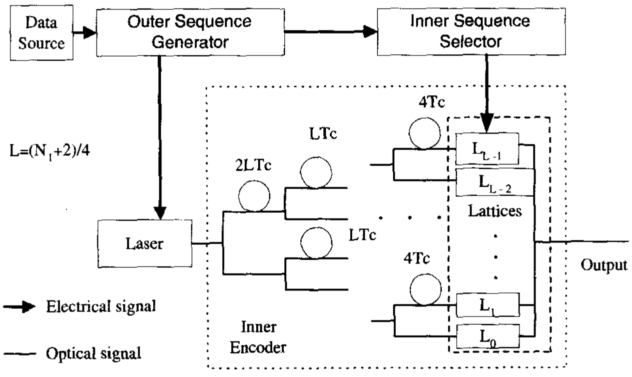

Fig. 1. Transmitter for optical fiber CDMA networks.

From the foregoing we conclude that for large networks a new strategy is required that would allow the use of large-weight codes but would avoid electronic processing at the chip rate. In this paper we propose the use of concatenated sequences formed by the Kronecker product [7] of two sequences of relatively large weight: Gold [8] and Lempel sequences [9], in incoherent optical fiber CDMA systems. The transmitter and receiver of the proposed network are described and the analysis of the BER performance of the system is presented. The BER is compared to that of another optical CDMA system. We find that, besides being practical the proposed system permits a large number of simultaneous users.

II. TRANSMITTER AND RECEIVER

Let $\{C_i(l)\}$ and $\{D_i(j)\}$ denote unipolar sequences of length N_1 and N_2, respectively. The sequence $\{A_i(m)\}$ of length $N = N_1N_2$ is a concatenated sequence made up of the inner sequence $\{C_i(l)\}$ and the outer sequence $\{D_i(j)\}$ if each "1" chip of $\{D_i(j)\}$ is encoded by another sequence $\{C_i(l)\}$ and each "0" chip of $\{D_i(j)\}$ is replaced by $\{C_i^c(l)\}$ which is the complement of $\{C_i(l)\}$ [7].

In the proposed system, the inner sequences consist of unipolar balanced Gold sequences generated by encoding each "1" chip of Gold sequences [8] by two chips "10" and each "-1" chip of the sequences by "01". The outer sequences are Lempel sequences, which are unipolar balanced sequences and can

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Manuscript received December 11, 2000; approved for publication by H. Vincent Poor, Division I Editor, May 23, 2001.

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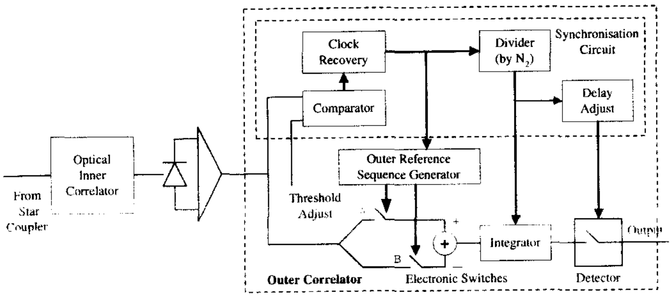

Fig. 2. Receiver for optical fiber CDMA networks.

be generated by a simple algorithm [9]. The spreading is implemented by sequence-inversion keying (SIK) whereby, each "1" data bit is replaced by a unipolar outer sequence while the complement of the sequence replaces each "0" bit. Each "1" chip of the outer sequence is represented by a unipolar inner sequence while the complement of this sequence is used for each "0" chip of the outer sequence. It has been shown in [2] that a balanced Gold sequence of length N_1 can be broken into $L = (N_1 + 2)/4$ blocks, where the first $L - 1$ blocks consist of four chips and the last block consists of two chips. The 4-chip combinations $(1010, 0101, 0110, 1001)$ and the 2-chip combinations $(01, 10)$ can be generated with a 2-stage programmable optical lattice consisting of one 3dB-coupler and two 2 × 2 electro-optic switches that can be switched from a 3dB-split state to the bar-state or cross state. Those lattices can be used to construct the transmitter as shown in Fig. 1. In this transmitter, outer sequences are electronically generated by the outer sequence generator and used to control the inner sequence selector. The laser generates a train of optical pulses of maximum pulse width T_c at the rate $1/T_o$ where $T_c = T/N$ is the chip duration of the concatenated sequences, T is the bit duration and $T_o = N_1 T_c$ is the chip duration of the outer sequences. The train of optical pulses is directed to the inner encoder where inner balanced Gold sequences are generated. This encoder is a parallel delay-line encoder consisting of $(N_1 + 2)/4$ branches providing delays $0T_c, 4T_c, \cdots, (N_1 - 2)T_c$ and each branch is connected to a lattice The inner sequence selection can be realized by controlling the setting of lattices L_k $(k = 0, 1, 2, \cdots, L - 1)$ so that the lattice can generate the kth block of the inner sequence. When there is a change from "1" to "0" or "0" to "1" in the outer sequence, the inner sequence selector generates signals for resetting each lattice allowing the inner encoder to generate complement sequences. Thus, the transmitter can be programmable to generate any sequence of the concatenated code.

The receiver structure is shown in Fig. 2 and consists of an optical inner correlator of the same structure as the inner encoder described above and an electronic outer correlator. In this receiver, the optical output of the inner correlator is converted into an electrical current in an avalanche photodiode (APD). After amplification this signal is fed to the outer correlator where it is split into two branches: One is to the synchronization circuit and the other is to two electronic switches A and B, which are switched by the outer reference sequence and its complement, respectively. These sequences are generated by the outer reference sequence generator, which is controlled by the synchronization circuit. The outputs of the switches are subtracted and the resulting signal is then integrated over a bit duration, sampled and detected with reference to zero threshold. The synchronization circuit is based on the detection of the peaks of the "inner" auto-correlation between the desired signal and the inner reference sequence. These peaks are detected by using a comparator with adjustable threshold and used for clock recovery.

It should be noted that with sequence-inversion keying and using the unipolar-bipolar correlator, the output of the receiver is equivalent to that of receivers used in bipolar radio CDMA systems. This allows us to make use of well-known CDMA codes published in the literature (Gold codes, Lempel codes, etc.) even though the encoding operation is based on optical sequences only.

III. PERFORMANCE ANALYSIS

We investigate an optical fiber CDMA network with K simultaneous users. Each user is assigned a fixed sequence serving as its reference. A user wishing to transmit data encodes its data by using the reference sequence of its intended receiver. The SIK optical signal at the output of the kth transmitter $(1 \leq k \leq K)$ can be written as

$$s_k(t) = P_k[B'_k(t)A'_k(t) + B'^c_k(t)A'^c_k(t)], \tag{1}$$

where P_k denotes the chip optical intensity of the kth user, $A'_k(t)$ and $A'^c_k(t)$ are the code waveform and its complement, and $B'_k(t)$, $B'^c_k(t)$ are the transmitted binary signal and its complement, respectively. The term $B'_k(t)$ is given by

$$B'_k(t) = \sum_{n=-\infty}^{\infty} B_k(n)\Pi_T(t - nT), \tag{2}$$

where $B_k(n)$ is the binary value (0 or 1) of the data bit in the nth bit interval of duration T, and $\Pi_T(t)$ is the unit amplitude unipolar rectangular pulse of duration T. The waveforms $A'_k(t)$ can be written as

$$A'_k(t) = \sum_{n=\infty}^{\infty} A_k(n)\Pi_{T_c}(t - nT_c), \tag{3}$$

where the sequence $\{A_k(n)\}$ of length N is the reference sequence of the intended receiver that is constructed from the inner sequence $\{C_k(l)\}$ of length N_1 and the outer sequence $\{D_k(j)\}$ of length N_2. $\Pi_{T_c}(t)$ is the unit amplitude unipolar rectangular pulse of duration $T_c = T/N$. Assume that every user transmits the same chip optical power and the received chip optical power is P_S for all k and the K simultaneous transmitters are not synchronized to each other. The total received optical signal $R_i(t)$ at the input of the ith receiver is the incoherent sum

$$R_i(t) = \sum_{k=1}^{K} P_S[B'_k(t-\tau_k)A'_k(t-\tau_k)+B'^c_k(t-\tau_k)A'^c_k(t-\tau_k)], \tag{4}$$

where τ_k is the transmission delay associated with the kth signal. The inner correlation of the received optical signal to the inner reference code waveform $C'_i(t)$ produces the optical signal $Z_i(t)$ at time $t = T_o = N_1 T_c$, and $Z_i(T_o)$ can be written as

$$Z_i(T_o) = \frac{1}{T_c}\int_0^{T_o} \frac{R_i(t)C'_i(t)}{S}dt, \tag{5}$$

where $S = (N_1+2)^2/4$ is the optical recombination loss factor of the receiver and $C'_i(t)$ is given by

$$C'_i(t) = \sum_{n=-\infty}^{\infty} C_i(n)\Pi_{T_c}(t-nT_c), \tag{6}$$

with $\{C_i(n)\}$ being the inner reference sequence of the ith user. The resulting optical signal is converted into an electrical current in an APD of responsivity $R(A/W)$ (at unit gain). The electrical signal is directed to the outer correlator that consists of two switches: One is switched by the outer reference waveform $D'_i(t)$ and the other is switched by its complement $D'^c_i(t)$ with $D'_i(t)$ being given by

$$D'_i(t) = \sum_{n=-\infty}^{\infty} D_i(n)\Pi_{T_o}(t-nT_o), \tag{7}$$

and $\{D_i(n)\}$ being the outer reference sequence of the ith user, and $\Pi_{T_o}(t)$ is the unit amplitude unipolar rectangular pulse of duration T_o. The current $i_i(t)$ at the output of the integrator at time $t = T$ is

$$\begin{aligned} i_i(T) = {} & \frac{P_S RM}{2S}\frac{1}{T_o}\int_0^T \{\frac{1}{T_c}\sum_{k=1}^{K}\int_0^{T_o}[B'_k(t-\tau_k)A'_k(t-\tau_k) \\ & +B'^c_k(t-\tau_k)A'^c_k(t-\tau_k)]C'_i(t)dt[D'_i(t)-D'^c_i(t)]\}dt \\ & +n(t), \end{aligned} \tag{8}$$

where M is the APD gain and $n(t)$ is the composite noise current composed of shot noise and thermal noise. For $1 \le k, i \le K$, we have

$$B'_k(t)A'_k(t) + B'^c_k(t)A'^c_k(t) = \frac{[1+b'_k(t)a'_k(t)]}{2}, \tag{9}$$

$$C'_i(t) = \frac{1+c'_i(t)}{2}, \quad D'_i(t) - D'^c_i(t) = d'_i(t). \tag{10}$$

Without loss of generality, we can normalize the delays to the delay τ_1 of the first transmitter and assume $0 \le \tau_k \le T$ for $1 \le k \le K$. Substitute (9) and (10) into (8) and note that both components of the concatenated sequences are balanced, (8) can be rewritten in the short form

$$i_i(t) = i_{(i,i)}(T) + \sum_{k=2}^{K} i_{(i,k)}(T) + n(t), \tag{11}$$

with

$$i_{(i,i)}(T) = \frac{P_S RM}{8S}b_1(0)N, \tag{12}$$

where $b_1(0)$ denotes the data bit which can be either "1" or "-1" and

$$\begin{aligned} i_{(i,k)}(T) = {} & \frac{P_S RM}{8S}\frac{1}{T_o}\int_0^T \{\frac{1}{T_c}\int_0^{T_o}[1+b'_k(t-\tau_k)a'_k(t-\tau_k)] \\ & \cdot[1+c'_k(t)]dt\}d'_i(t)dt. \end{aligned} \tag{13}$$

(12) shows the desired signal and (13) represents the multiple-access interference (MAI) caused by the kth user at the receiver of the ith user. For large K and N, we may model all the MAI terms as a zero-mean Gaussian process. The variance of the total MAI, derived in the Appendix, can be approximately calculated by

$$\begin{aligned} \sigma_S^2 \approx {} & [\frac{P_S RM}{8S}]^2\frac{1}{3N}\sum_{k=2}^{K}\sum_{m_k=1-N}^{N-1}\{2[C_{a_k,a_i}(m_k)]^2 \\ & +C_{a_k,a_i}(m_k)C_{a_k,a_i}(m_k+1)\}, \end{aligned} \tag{14}$$

where $C_{a_i,a_k}(\cdot)$ is the discrete aperiodic cross-correlation function for sequences $\{a_k(m)\}$ and $\{a_i(m)\}$. The shot noise in the photodiode can be approximated by Gaussian statistics. The variance of the shot noise generated by the APD can be calculated by [10]:

$$\sigma_{sh}^2 = 2qM^2F_A(i_m + i_D)B,$$

where $q = 1.602 \times 10^{-19}C$ is the electric charge, i_m is the mean value of the photo-current, i_D is the dark current, B is the noise-equivalent receiver bandwidth and F_A is the excess noise factor of the APD and is given by

$$F_A = k_A M + (1-k_A)(2-1/M),$$

where k_A is the APD effective ionization ratio. The mean value of photocurrent is

$$i_m = \frac{KRP_SN_1}{8S}.$$

Therefore, the variance of the shot noise due to the APD can be evaluated to be

$$\sigma_{sh}^2 = 2qM^2F_AB\left(\frac{KRP_SN_1}{8S} + i_D\right).$$

The thermal noise can be also modeled as a Gaussian random process and the variance of the thermal noise is

$$\sigma_T^2 = \frac{4k_BT_TB}{R_L},$$

where $k_B = 1.38 \times 10^{-23}J/°K$ is the Boltzmann's constant, T_T is the receiver noise temperature and R_L is the receiver load resistor. By assuming all the noise processes to be independent the total noise power is simply the sum of the variances

$$\sigma_N^2 = 2qM^2F_AB\left(\frac{KRP_SN_1}{8S} + i_D\right) + \frac{4k_BT_TB}{R_L}. \tag{15}$$

The possible errors in the received bit stream occur at the detector which compares the input signal level to a preset threshold level and issues a bit "1" or "0" depending on whether the sampled level is above or below the threshold, respectively. For the proposed optical fiber CDMA network the optimum detection threshold is zero and the BER is given by [10]:

$$\text{BER} = \frac{1}{2}erfc[\frac{i_1 - i_0}{\sqrt{2}(\sigma_1+\sigma_0)}], \tag{16}$$

Table 1. Typical laser link parameters.

Name	Symbol	Value
APD responsivity (at unit gain)	R	0.84 A/W
APD gain	M	100
APD effective ionization rate	k_A	0.02
APD dark current	i_D	1 nA
Receiver load resistor	R_L	50 Ω
Laser pulse width	T_c	0.03 ns
Receiver noise temperature	T_T	300 °K

where i_1, i_0 and σ_1, σ_0 are the average values and the standard deviations of the sampled currents for bits "1" and bit "0", respectively; $efrc(x)$ is the complementary error function, defined as

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-\lambda^2} d\lambda.$$

For the proposed system $i_1 = -i_0$ and $\sigma_1 = \sigma_0$, therefore, (16) can be written as

$$\text{BER} = \frac{1}{2} erfc[\frac{i_1}{\sqrt{2}\sigma_1}],$$

where i_1 is calculated using (12) with $b_1(0) = 1$ and $\sigma_1 = \sqrt{\sigma_s^2 + \sigma_N^2}$.

Finally, the BER can be approximated by:

$$\text{BER} = \frac{1}{2} erfc[\frac{P_S RMN}{8S\sqrt{2(\sigma_S^2 + \sigma_N^2)}}].$$

IV. COMPARISON TO OTHER OCDMA SYSTEMS

We compare the proposed system with the incoherent optical fiber CDMA system using optical orthogonal codes (OOCs), parallel delay line correlator with double hard-limiters and APD [6]. At first, it should be noted that the receiver for OOC sequences is of fixed reference sequence (i.e., non-programmable) while the proposed receiver is fully programmable. The BER performance of both systems is calculated as a function of the received chip optical power $P_S \in (-50 \text{ dBm}, 0 \text{ dBm})$. Concatenated sequences of length $N = 1008$ generated from balanced Gold sequences of length $N_1 = 14$ as inner sequences and Lempel sequences of length $N_2 = 72$ as outer sequences are used for the proposed receiver. In order to have a fair comparison both systems should use code sequences of approximately same lengths. Hence, we calculate the BER of the system using OOC sequences of length $N = 1023$ and weight $W = 5$ using equation (56) of [6]. The other parameters, which are the same as those used in [6] are shown in Table 1. Note that both systems operate at a data bit rate of about 32.5 Mb/s because laser pulse width $T_c = 0.03$ ns is used for both systems. It is found that the system using concatenated codes can support a maximum of 40 simultaneous users at BER $= 10^{-9}$ whereas the systems using OOCs can support a maximum of 10 simultaneous users at the same BER. This is illustrated in Fig. 3 where we show the BER versus the received chip optical power of two systems. It can be seen that for a BER $= 10^{-9}$ and $K = 10$ the proposed system requires a chip optical power of -42 dBm while for the system using OOCs a higher chip optical power of -28 dBm is required. If the number of simultaneous users increases to 40 the proposed system still can achieve BER $= 10^{-9}$ with a received chip optical power of -24 dBm, while the performance of the system using OOCs is limited at BER $= 2 \times 10^{-5}$. Concatenated codes also provide a larger number of sequences in a set. There are 216 sequences in the set of concatenated sequences of length $N = 1008$ [4], while the maximum number of available OOC sequences of length $N = 1023$ and weight $W = 5$ is $(N - 1)/[W(W - 1)] = 51$ [5].

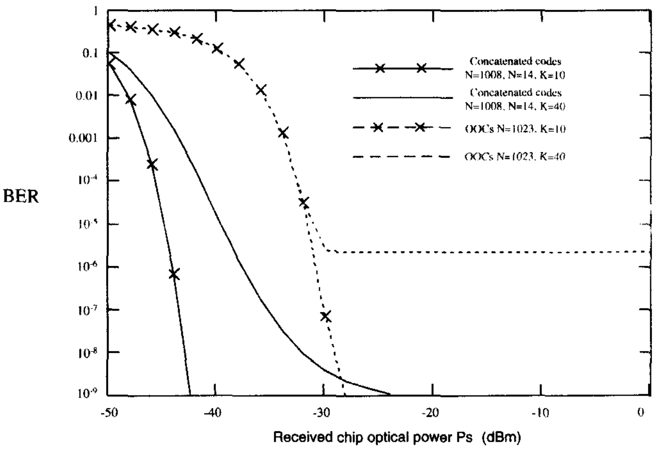

Fig. 3. BER of the proposed receiver in comparison to the receiver using OOCs.

V. CONCLUSIONS

We have proposed an optical fiber CDMA system in which the extensive signal-processing capabilities of electronics have been combined with the high-speed capabilities of all-optical signal processing. The bit-error rate of the system in the presence of noise and multiple-access interference has been evaluated and compared to the incoherent optical fiber CDMA system using optical orthogonal codes, parallel delay line correlator with double hard-limiters and APD. It has been found that the proposed system using concatenated codes can support a maximum of 40 simultaneous users at BER $= 10^{-9}$ whereas the systems using OOCs can support a maximum of 10 simultaneous users at the same BER. In addition, for the same number of simultaneous users, the proposed system requires a lower received chip optical power for achieving the same BER as that of the system using OOCs. Finally, concatenated codes provide a larger number of sequences in a set of sequences of approximately the same lengths. Therefore, the system using concatenated codes can have a larger number of potential subscribers.

APPENDIX

In this appendix, the variance of the total multiple access interference (MAI) at the receiver of the ith user is derived. Since the component sequences of concatenated sequences are balanced, (13) representing the MAI caused by the kth user at the receiver of the ith user can be simplified and written as

$$i_{(i,k)}(T) = \frac{P_S RM}{8ST_c}[i^a_{(i,k)}(T) + i^d_{(i,k)}(T)], \tag{17}$$

where

$$i^d_{(i,k)}(T) = \sum_{m=0}^{N-1} \int_{mT_c}^{(m+1)T_c} b'_k(t-\tau_k)a'_k(t-\tau_k)d'_i(t)dt, \tag{18}$$

and

$$i^a_{(i,k)}(T) = \sum_{m=0}^{N-1} \int_{mT_c}^{(m+1)T_c} b'_k(t-\tau_k)a'_k(t-\tau_k)c'_i(t)d'_i(t)dt. \tag{19}$$

There is no loss of generality in assuming that τ_k is uniformly distributed on the interval $[0,T]$ for $2 \le k \le K$ and τ_k can be expressed by $\tau_k = (l_k + j_k N_1)T_c + \delta_k$ where $0 \le m_k = l_k + j_k N_1 \le N-1$ with l_k and j_k being integers such that $0 \le l_k \le N_1 - 1, 0 \le j_k \le N_2 - 1, N_1 N_2 = N$ and δ_k are real values in the range $0 \le \delta_k \le T_c$. Substituting τ_k into (18), (19) we found that

$$i_{(i,k)}(T) = \frac{P_s RM}{8S}[b_k(-1)F_{(i,k)}(m_k) + b_k(0)F'_{(i,k)}(m_k)], \tag{20}$$

where $b_k(-1)$ and $b_k(0)$ are the consecutive data bits emitted by the kth user, $F_{(i,k)}(m_k)$ and $F'_{(i,,k)}(m_k)$ are defined by

$$\begin{aligned} F_{(i,k)}(m_k) &= \frac{\delta_k}{T_c}\{c_k(N_1 - l_k - 1)[C_{d_i,d_k}(j_k + 1 - N_2) \\ &\quad -C_{d_i,d_k}(j_k - N_2)] + C_{a_i,a_k}(m_k + 1 - N) \\ &\quad -C_{a_i,a_k}(m_k - N)\} + S(l_k)[C_{d_i,d_k}(j_k + 1 - N_2) \\ &\quad -C_{d_i,d_k}(j_k - N_2)] + C_{a_i,a_k}(m_k - N), \quad (21) \\ F'_{(i,k)}(m_k) &= \frac{\delta_k}{T_c}\{c_k(N_1 - l_k - 1)[C_{d_i,d_k}(j_k + 1) \\ &\quad -C_{d_i,d_k}(j_k)] + C_{a_i,a_k}(m_k + 1) - C_{a_i,a_k}(m_k)\} \\ &\quad +S(l_k)[C_{d_i,d_k}(j_k + 1) - C_{d_i,d_k}(j_k)] + C_{a_i,a_k}(m_k), \quad (22) \end{aligned}$$

where $C_{a_i,a_k}(\cdot)$ and $C_{d_i,d_k}(\cdot)$ are the discrete aperiodic cross-correlation functions for sequences $\{a_i(m)\}$, $\{a_k(m)\}$ and $\{d_i(j)\}$ and $\{d_k(j)\}$, respectively, and $S(l_k)$ is the sum of the first $(N_1 - l_k)$ chips of sequence $\{c_k(l)\}$.

The interference $i_{(i,k)}(T)$ is modeled as a Gaussian process with a probability distribution function of mean value $M_{(i,k)}$ and variance $\sigma^2_{(i,k)}$. Since $b_k(-1)$, $F_{(i,k)}(m_k)$ and $b_k(0)$, $F'_{(i,k)}(m_k)$ are pairs of mutually independent random variables and $b_k(-1)$ and $b_k(0)$ are zero-mean independent random variables with equal probable "1" and "-1" outcomes, the mean value $M_{(i,k)}$ is equal to zero. Consequently, the variance $\sigma^2_{(i,k)}$ can be evaluated by

$$\sigma^2_{(i,k)} = [\frac{P_S RM}{8S}]^2\{E\{[F_{(i,k)}(m_k)]^2\} + E\{[F'_{(i,k)}(m_k)]^2\}\}, \tag{23}$$

where $E[X^2]$ is the expectation of the random variable X. Using (21), (22) into (23) the variance $\sigma^2_{(i,k)}$ is given by

$$\begin{aligned} \sigma^2_{(i,k)} &= [\frac{P_S RM}{8S}]^2 \frac{1}{3N} \sum_{m_k=1-N}^{N-1} \{2[C_{a_i,a_k}(m_k)]^2 \\ &\quad +C_{a_i,a_k}(m_k)C_{a_i,a_k}(m_k + 1) \\ &\quad +\{c_k(N_1 - l_k - 1)[2\hat{\theta}_{c_i,c_k}(l_k + 1) + \hat{\theta}_{c_i,c_k}(l_k)] \\ &\quad +3S(l_k)[\hat{\theta}_{c_i,c_k}(l_k + 1) + \hat{\theta}_{c_i,c_k}(l_k) - 2S(l_k - 1)] - 2\} \\ &\quad \cdot\{C_{d_i,d_k}(j_k)C_{d_i,d_k}(j_k + 1) - [C_{d_i,d_k}(j_k)]^2\}\}, \end{aligned}$$

where $\hat{\theta}_{c_i,c_k}(\cdot)$ is the discrete odd cross-correlation function for sequences $\{c_k(l)\}$, $\{c_i(l)\}$. For evaluating the BER we approximate $\sigma^2_{(i,k)}$ by

$$\sigma^2_{(i,k)} \approx \frac{1}{3N} \sum_{m_k=1-N}^{N-1} \{2[C_{a_i,a_k}(m_k)]^2 + C_{a_i,a_k}(m_k)C_{a_i,a_k}(m_k+1)\}$$

The total MAI caused by $K-1$ transmitters at the receiver of the ith user can be modelled as the sum of $K-1$ independent randomly distributed Gaussian processes, hence, the variance of the total MAI may be approximately calculated by

$$\begin{aligned} \sigma^2_S &\approx [\frac{P_S RM}{8S}]^2 \frac{1}{3N} \sum_{k=2}^{K} \sum_{m_k=1-N}^{N-1} \{2[C_{a_k,a_i}(m_k)]^2 \\ &\quad +C_{a_k,a_i}(m_k)C_{a_k,a_i}(m_k + 1)\}. \quad (24) \end{aligned}$$

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers who gave valuable comments.

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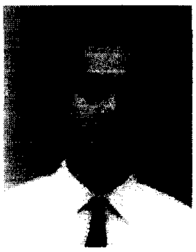

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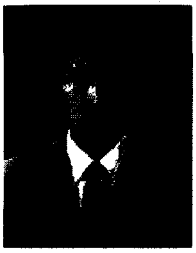

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