Improved Fiber Bragg Grating Array OFFH-CDMA System Using a Novel Frequency-Overlapping Multigroup Method

Wei-Ren Peng, Wen-Piao Lin, *Member, IEEE*, and Sien Chi, *Fellow, OSA*

Abstract—**The authors propose a novel frequency-overlapping multigroup scheme for a passive all-optical fast-frequency hopped code-division multiple-access (OFFH-CDMA) system based on fiber Bragg grating array (FBGA). In the conventional scheme, the users are assigned those codes constructed on the nonoverlapping frequency slots, and therefore the bandgaps between the adjacent gratings are wasted. To make a more efficient use of the optical spectrum, the proposed scheme divided the users into several groups, and assigned the codes, which interleaved to each other to the different groups. In addition to the higher utilization of the spectrum, the interleaved nature of the frequency allocations of different groups will make the groups less correlated and, hence, lower the multiple-access interference (MAI). The corresponding codeset and its constraints for this new scheme are also developed and analyzed. The performance of the system in terms of the correlation functions and bit error rate (BER) are given in both the conventional and the proposed schemes. The numerical results show that, with the multigroup scheme, performance is much improved compared to the conventional scheme.**

Index Terms—**Fiber Bragg grating array (FBGA), multiple-access interference (MAI), optical fast-frequency hopping code-division multiple access (OFFH-CDMA).**

I. INTRODUCTION

SPREAD-SPECTRUM code-division multiple access (CDMA) has been widely used for wireless communications. Due to its many advantages over traditional multiple-access schemes such as TDMA or FDMA, which are scheduled in time or frequency domains, CDMA provides advantages such as larger capacity, asynchronous access, frequency diversity, soft handover, etc. Due to the successful development of wireless CDMA, the use of CDMA in the optical domain has attracted a great deal of research recently. In the late 1970s, the first work on optical CDMA proposed using the fiber delay lines for optical processing, which is a scheme of direct-sequence CDMA (DS-CDMA) [1]. Alternative implementations of DS-CDMA are implemented by optical delay lines [2]–[4], ladder networks [5], [6], tunable delay lines [7]–[9], and recently, superstructure fiber Bragg grating (SSFBG) [10]–[12]. SSFBG provides not only a low-cost en/decoder but also high-speed optical processing. The shortcoming of this device is its lower power efficiency since the en/decoding grating must be weakly coupled.

In addition to the DS-CDMA, frequency-encoded CDMA (FE-CDMA) which encodes the signature code on the wavelength domain with coherent or noncoherent method was proposed and analyzed in [13]–[15]. Since the en/decoding process of these schemes is addressed with a bulk grating, the huge size of the transmitter/receiver is a problem. Although this problem has been resolved using two compact consecutive FBGs [16], the system still requires an ultrashort pulse generator and this will make the system high price. An alternate scheme sending colored pulses in a predetermined order is the optical fast-frequency hopping CDMA (OFFH-CDMA). The first FFH-CDMA in optical domain is proposed by using an optical frequency synthesizer as the encoder [17], [18]. The tunable FBG arrays (FBGA) are used instead of the frequency synthesizer to reduce further the transmitter cost [19]–[22]. Since the OCDMA is proposed as an access scheme in a local area network (LAN), an OFFH-CDMA system using the FBGA [19] that maintains high performance and potentially low cost is one of the best choices. However, due to the nonfully orthogonality of the optical codes, the maximum capacity is still limited by the multiple-access interference (MAI). Therefore, the emerging work for an OFFH-CDMA system is to reduce the MAI and increase the system capacity. Aimed at this, we propose a new scheme that can lessen the MAI of an OFFH-CDMA system.

In this paper, we propose a frequency-overlapping multigroup scheme that reduces the system MAI and enhances the maximum number of the coactive users. This scheme divides the users into different groups and assigns the users in each group with the frequency slots that are partially overlapping among different groups. Since this assignment makes a more efficient use of the optical spectrum than the conventional scheme, in which the frequency gap between any two adjacent Gaussian-shaped frequency slots is wasted, the performance is expected to be improved.

The rest of this paper is organized as follows. In Section II, we describe the frequency-allocation method in a conventional OFFH-CDMA scheme using the FBGA, and then our newly proposed method, which employs a frequency-overlapping

Manuscript received September 30, 2004; revised November 19, 2005. This work was supported in part by the National Science Council of R.O.C. under Contract NSC 93-2752-E-009-004-PAE, NSC 93-2752-E-007-002-PAE, NSC 94-2215-E-155-001, NSC 94-2215-E-155-003, and NSC 94-2215-E-009-006.

W.-R. Peng is with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan 300, R.O.C. (e-mail: pwr.eo92g@nctu.edu.tw).

W.-P. Lin is with the Department of Electrical Engineering, Chang-Gung University, Tao Yunan, Taiwan 333, R.O.C.

S. Chi is with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan 300, R.O.C., and also with the Department of Electrical Engineering, Yuan Ze University, Chung Li, Taiwan 320, R.O.C.

Digital Object Identifier 10.1109/JLT.2005.864003

0733-8724/$20.00 © 2006 IEEE

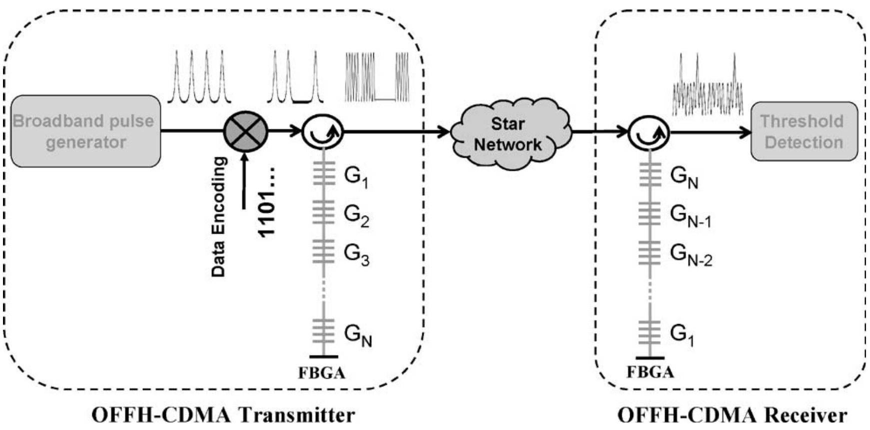

Fig. 1. OFFH-CDMA transmitter and receiver pair with the FBGA as an en/decoder.

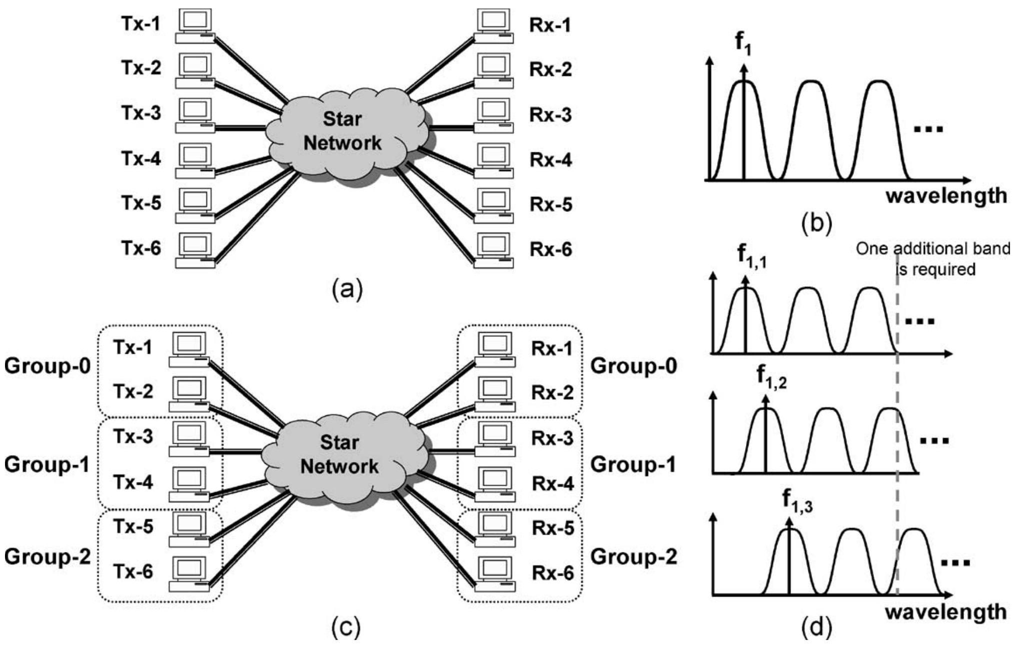

Fig. 2. (a) Star network with the conventional scheme. (b) Frequency allocation of the conventional scheme. (c) Star network with our proposed multigroup scheme. (d) Frequency allocation of the proposed multigroup scheme.

multigroup method. In Section III, we analyze the system performance through the development of the codes. We give the codes modified from the previous one-coincident sequence and their constraints for this new scheme. The system performance, in terms of the signal to interference ratio (SIR) and the probability of error, is analytically derived from these new codes. In Section IV, we show the numerical results of auto- and cross-correlation functions and the probability of error with different number of groups. It is found that the bit error rate (BER) or the maximum number of coactive users will be improved or enhanced by increasing the number of groups. Finally, our conclusions are given in Section V.

II. PROPOSED FREQUENCY-OVERLAPPING MULTIGROUP SCHEME

Fig. 1 shows the architecture of an OFFH-CDMA transmitter and receiver pair. A broadband light source is firstly data modulated using the amplitude shift keying (ASK) format and then encoded by the FBGA, where G_i is the frequency passband of each grating. The matched receiver recovers the transmitted data with a reciprocal FBGA. Optical power received from other transmitters will be randomized and treated as interference. Although there are some other candidates, such as array waveguide gratings (AWGs) or thin-film fillers can employ the OFFH-CDMA system and possibly can apply the scheme we proposed in this paper, it seems that FBGA is the simplest and cost-saving method to modulate and demodulate an OFFH-CDMA signal. Often, the MAI is the dominant factor limiting the number of the coactive user and the performance of a CDMA system, the emerging work for OCDMA is the reduction of the MAI level.

Fig. 2(a) shows a typical star network of a conventional scheme. All the users are assigned those codes constructed on the discrete nonoverlapping frequency slots, i.e., all the codes used in this network are mapped to the frequency slots shown in Fig. 2(b). Each user is assigned a specified hopping sequence $C(l)$ with a code length of N. $C(l)$ is the lth chip chosen from

0 to $q-1$, where q is the number of available nonoverlapping frequency slots. The hopping frequency $f_h(l)$ of the lth chip can be written as

$$f_h(l) = f_1 + f_{\text{offset}}(l) \tag{1}$$

where f_1 is the frequency of the first slot, and

$$f_{\text{offset}} = C(l)\frac{B}{q} \qquad l=1,\ldots,N, \text{ and } 0 \le C(l) \le q-1 \tag{2}$$

is the frequency offset around f_1. B is the total optical bandwidth and B/q is the interval of the frequency slots. This frequency allocation is direct and simple, coming from the ideas of the independent wavelength allocation in a wavelength division multiplexing (WDM) system. However, the spectrum efficiency is low since no usage is taken around the band gaps between any two consecutive frequency slots. The band gaps can be fully used with our multigroup scheme.

In the new scheme, the users are firstly divided into several groups, as shown in Fig. 2(c). The first group uses the same frequency allocation as the conventional scheme, in which the frequency slots are discrete and nonoverlapping. With a slightly upshift of the frequency allocation of the first group, we can obtain the allocation of the second group. The allocation of the third group can be obtained further by up-shifting the allocation of the second group, and so on. The frequency allocation is shown in Fig. 2(d). The first frequency slots of different groups are assigned as

$$f_{1,j} = f_1 + j\frac{B}{N_{\text{g}}q} \qquad 0 \le j \le N_{\text{g}} - 1 \tag{3}$$

where $f_{1,j}$ is the first frequency slot of the jth group, and N_{g} is the total group number. The corresponding hopping frequency in the jth group can be written as

$$f_{h,j}(l) = f_1 + \frac{B}{q}\left(C_j(l) + \frac{j}{N_{\text{g}}}\right) = f_1 + \frac{B}{N_{\text{g}}q}\left(N_{\text{g}}C_j(l) + j\right). \tag{4}$$

This formula can be explained as that all users use the same first slot f_1 with the modified code pattern of $N_{\text{g}}C_j(l)+j$ multiplier the slot width $B/(N_{\text{g}}q)$. However, an additional slot with a width of $(B \times j)/(N_{\text{g}}q)$ is required in this new scheme. Since the distribution of the frequency slots is more uniform than the conventional scheme, better spectra efficiency is expected. In addition, the reduced overlapping area of the frequency slots between any two different groups implies less correlation, thus lessening the MAI. To promise that all the users can communicate with all the other users, each transceiver should equip with a tunable en/decoder.

III. PERFORMANCE ANALYSIS

A. Hamming Auto- and Cross-Correlation

Multilevel sequences are used to specify which frequency will be used for transmission at any given time. An important requirement in multiple-access applications is to keep the mutual interference as small as possible. The interference is generated by the cross-correlation function of the hopping sequences. One of the correlation function measurements is the periodic Hamming cross-correlation function H_{XY}, which is defined as

$$H_{XY}(\tau) = \sum_{i=0}^{N-1} h\left(C_X[i], C_Y[i+\tau]_{\bmod N}\right), \qquad \text{for } 0 \le \tau < N \tag{5}$$

where

1) $h(a,b) = \begin{cases} 0, & \text{if } a \ne b \\ 1, & \text{if } a = b \end{cases}$
2) $C_X = (C_X[0], C_X[1], \ldots, C_X[N-1])$ and $C_Y = (C_Y[0], C_Y[1], \ldots, C_Y[N-1])$ denote two hopping sequences of length N.
3) C_X and $C_Y \in \{f_1, f_2, \ldots, f_q\}$, where f_i is one of the q available frequency slots $(q \ge N)$.

The function $H_{XY}(\tau)$ represents the number of the same frequency slots from any two sequences with relative time delay of τ. We will use it to analyze the performance of the developed FFH codes. If $H_{XY}(\tau) \le 1$ for any $X \ne Y$, this code set is called as one-coincidence sequence [23], and this gives the smallest interference in an OFFH-CDMA system.

B. Codes for This New Scheme

To promise a better performance of this new scheme, in addition to the previous work [24], there are two more constraints should be carefully concerned. First, there should not be any two frequency slots of a specific user with a difference smaller than N_{g}. This allows the gratings in an FBGA independent to each other and, hence, promises the uniform output chip power after encoded by the FBGA. Second, the new code should still exhibit the so-called one-coincidence property. However, since the frequency slots in the new scheme are interleaved with each other, instead of the one coincidence, the partial coincidence should be considered. The partial coincidence will be defined later.

For the new scheme, the number of conventional usable discrete frequency slots q is increased to $N_{\text{g}}q$ frequency slots with an interval of $B/(N_{\text{g}}q)$. Since the bandwidth of a grating and their intervals used in the conventional scheme are approximately equal to B/q, the new interval of $B/(N_{\text{g}}q)$ will induce the adjacent N_{g} frequency slots to overlap. We choose N as the code weight from the available frequency slots q, where $N \le q$. The code generator can be derived as [24] $C = \{C_0, C_1, \ldots, C_{N-1}\}$, where C_i is the element of integers of $d+1, d+2, \ldots, q-d-1$, $d = (q-N-1)/2$, for q odd integers, and $d = (q-N-2)/2$ for q even integers. The new codes can be generated as follows:

$$F_{i,j}(k) = G_{i,j}(k) \times N_{\text{g}} + j, \qquad 0 \le i \le M-1$$
$$0 \le j \le N_{\text{g}} - 1, \qquad 0 \le k \le N-1 \tag{6}$$

where we have the following.

1) $F_{i,j}(k)$ is the kth chip of the ith user in the jth group.
2) $G_{i,j}(k) = [D_0(k) + i + M \times j]_{\bmod q}$, and $M = (q-1)/N_{\text{g}}$ is the number of codes in each group.

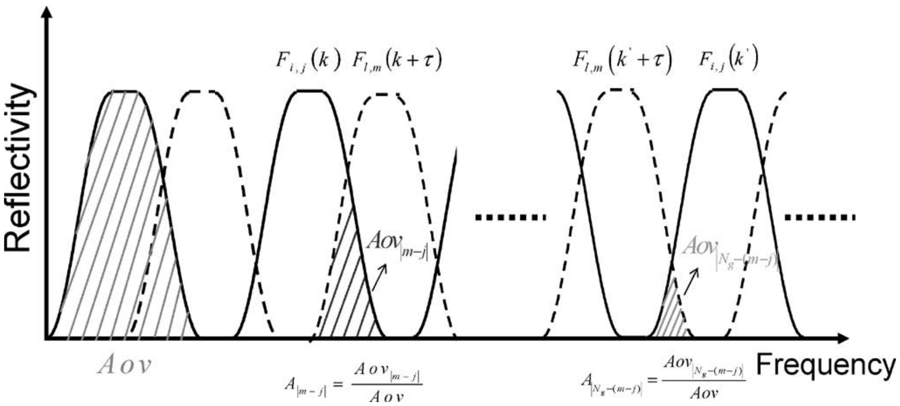

Fig. 3. Frequency slots of two different groups: ith and jth group. The area of the whole grating is denoted as Aov, which is the whole reflective power of a grating. The two overlapping areas denoted as $A_{|m-j|}$ and $A_{|N_\mathrm{g}-(m-j)|}$ are the normalized interference of the proposed scheme with the new codes.

3) $D_0(k) = [C_0 + C_1 + \cdots C_{k-1}]_{\bmod q}$.

Note that the range of k here is located within $[0, N-1]$ rather than $[1, N]$ defined in [24].

The difference of any two frequency slots of a specific user can be written as

$$\begin{aligned} D_{i,j}(k_1, k_2) &= |F_{i,j}(k_1) - F_{i,j}(k_2)| \\ &= N_\mathrm{g}\,|G_{i,j}(k_1) - G_{i,j}(k_2)|\,. \end{aligned} \tag{7}$$

It is known that $|G_{i,j}(k_1) - G_{i,j}(k_2)| \geq 1$ for $k_1 \neq k_2$, and hence, the difference $D_{i,j}(k_1, k_2)$ should be larger than N_g. Thus, any two slots in a sequence will differ by at least N_g, and the uniform output chip power can be promised.

To ensure that the performance of the new scheme outperforms the conventional scheme, the developed codeword should also exhibit the one-coincidence property. Clearly, for any two codes from the same group, the one-coincidence nature still holds. However, if the two codes are from different groups, the partial coincidence should be considered. We assume that there are two codes from the jth and the mth groups $(0 \leq j < m < N_\mathrm{g})$, respectively. From (6), the partial hit occurs only when the difference of two frequency slots is $(m-j)$ or $N_\mathrm{g} - (m-j)$. We consider the following two Hamming functions:

$$\begin{aligned} H_1(\tau) &= \sum_{k=0}^{N-1} h\left(F_{i,j}(k) + (m-j), F_{l,m}(k+\tau)\right) \\ &= \sum_{k=0}^{N-1} h\left(G_{i,j}(k), G_{l,m}(k+\tau)\right) \leq 1 \end{aligned} \tag{8}$$

and

$$\begin{aligned} H_2(\tau) &= \sum_{k'=0}^{N-1} h\left(F_{i,j}(k') - [N_\mathrm{g} - (m-j)], F_{l,m}(k'+\tau)\right) \\ &= \sum_{k'=0}^{N-1} h\left(G_{i,j}(k'), G_{l+1,m}(k'+\tau)\right) \leq 1. \end{aligned} \tag{9}$$

The corresponding relations and the overlapping areas, which represent the reflective interference power, are shown in Fig. 3. The two equations (8) and (9) indicate that the normalized maximum interference power of the two sequences is $H_1(\tau)A_{|m-j|} + H_2(\tau)A_{|N_\mathrm{g}-(m-j)|}$, which we defined as the partial coincidence. Note that the shadowing areas $A_{|m-j|}$ and $A_{|N_\mathrm{g}-(m-j)|}$, as shown in Fig. 3, are normalized to the whole reflective power of grating A_{0v}. Since the sum of $A_{|m-j|}$ and $A_{|N_\mathrm{g}-(m-j)|}$ is not greater than 1, i.e., $A_{|m-j|} + A_{|N_\mathrm{g}-(m-j)|} \leq 1$, the partial coincidence is always not greater than 1, i.e., $H_1(\tau)A_{|m-j|} + H_2(\tau)A_{|N_\mathrm{g}-(m-j)|} \leq 1$. Since the codes developed above are with this property, the better performance of the new scheme can be promised. The maximum of the partial-coincidence $H_1(\tau)A_{|m-j|} + H_2(\tau)A_{|N_\mathrm{g}-(m-j)|} = 1$ holds only when the gratings are with ideal rectangle-shaped spectra.

For example, we construct the 2-group codes with $N = 12$ and $q = 25$. The generator sequence is $C = \{12, 17, 16, 15, 7, 11, 13, 8, 9, 10, 18, 14\}$; the 2-group codes are derived as follows:

$$\text{Group 0}\left\{\begin{array}{cccccccccccc} 24 & 8 & 40 & 20 & 34 & 6 & 32 & 48 & 16 & 36 & 22 & 0 \\ 26 & 10 & 42 & 22 & 36 & 8 & 34 & 0 & 18 & 38 & 24 & 2 \\ 28 & 12 & 44 & 24 & 38 & 10 & 36 & 2 & 20 & 40 & 26 & 4 \\ 30 & 14 & 46 & 26 & 40 & 12 & 38 & 4 & 22 & 42 & 28 & 6 \\ 32 & 16 & 48 & 28 & 42 & 14 & 40 & 6 & 24 & 44 & 30 & 8 \\ 34 & 18 & 0 & 30 & 44 & 16 & 42 & 8 & 26 & 46 & 32 & 10 \\ 36 & 20 & 2 & 32 & 46 & 18 & 44 & 10 & 28 & 48 & 34 & 12 \\ 38 & 22 & 4 & 34 & 48 & 20 & 46 & 12 & 30 & 0 & 36 & 14 \\ 40 & 24 & 6 & 36 & 0 & 22 & 48 & 14 & 32 & 2 & 38 & 16 \\ 42 & 26 & 8 & 38 & 2 & 24 & 0 & 16 & 34 & 4 & 40 & 18 \\ 44 & 28 & 10 & 40 & 4 & 26 & 2 & 18 & 36 & 6 & 42 & 20 \\ 46 & 30 & 12 & 42 & 6 & 28 & 4 & 20 & 38 & 8 & 44 & 22 \end{array}\right.$$

$$\text{Group 1}\left\{\begin{array}{cccccccccccc} 49 & 33 & 15 & 45 & 9 & 31 & 7 & 23 & 41 & 11 & 47 & 25 \\ 1 & 35 & 17 & 47 & 11 & 33 & 9 & 25 & 43 & 13 & 49 & 27 \\ 3 & 37 & 19 & 49 & 13 & 35 & 11 & 27 & 45 & 15 & 1 & 29 \\ 5 & 39 & 21 & 1 & 15 & 37 & 13 & 29 & 47 & 17 & 3 & 31 \\ 7 & 41 & 23 & 3 & 17 & 39 & 15 & 31 & 49 & 19 & 5 & 33 \\ 9 & 43 & 25 & 5 & 19 & 41 & 17 & 33 & 1 & 21 & 7 & 35 \\ 11 & 45 & 27 & 7 & 21 & 43 & 19 & 35 & 3 & 23 & 9 & 37 \\ 13 & 47 & 29 & 9 & 23 & 45 & 21 & 37 & 5 & 25 & 11 & 39 \\ 15 & 49 & 31 & 11 & 25 & 47 & 23 & 39 & 7 & 27 & 13 & 41 \\ 17 & 1 & 33 & 13 & 27 & 49 & 25 & 41 & 9 & 29 & 15 & 43 \\ 19 & 3 & 35 & 15 & 29 & 1 & 27 & 43 & 11 & 31 & 17 & 45 \\ 21 & 5 & 37 & 17 & 31 & 3 & 29 & 45 & 13 & 33 & 19 & 47 \end{array}\right.$$

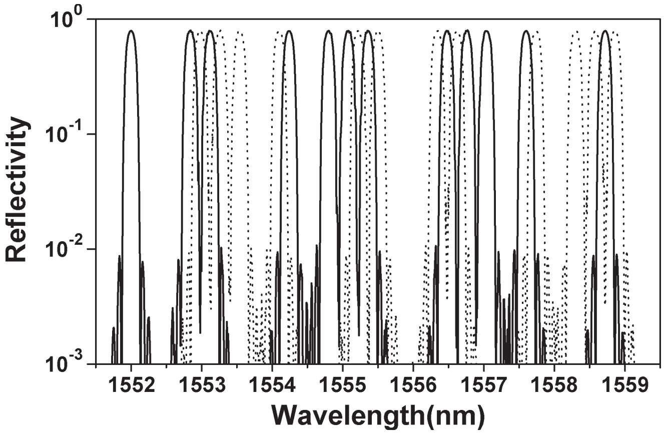

Fig. 4. FBGA spectra of the 2-group codes. Codes from different groups are overlapping. The solid line is for group 0, and the dashed line is for group 1.

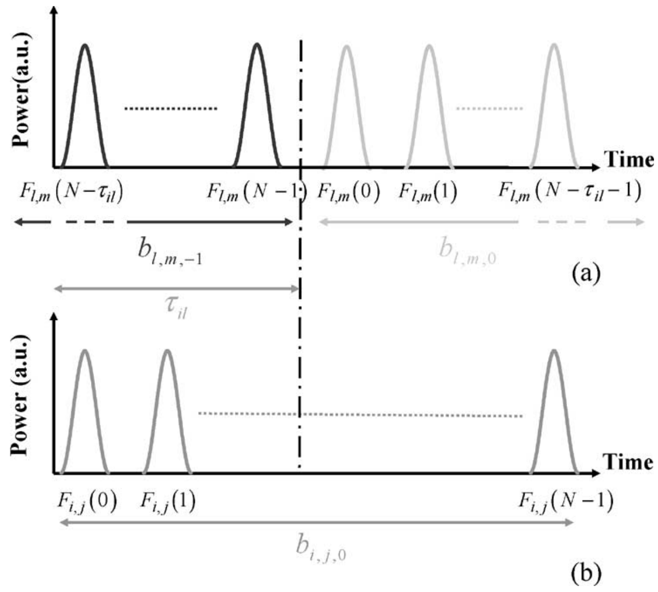

Fig. 5. Received signals at the ith receiver from the jth group. (a) Interference data of the lth transmitter from the mth group. The used code is denoted as $F_{l,m}$. (b) Input signal of the desired transmitter: the ith transmitter from the jth group. The used code is denoted as $F_{i,j}$. "$b_{l,m,n}$" is the previous or the present data bit of the lth transmitter from the mth group when $n = -1$ or $n = 0$. τ_{il} represents the relative delay chips between the two inputs.

From the construction rules, we find that the codes of the first group are the same as that of the previously developed in [24] multiplying the group number by N_{g}. Fig. 4 shows the FBGA spectra of the first codeword of group 0 and group 1 as solid and dashed lines, respectively. Codewords for other different number of groups can be derived by the same method.

C. Signal to Interference Ratio (SIR)

Interference will occur when two or more interfered slots and the desired slot with a difference smaller than N_{g} reach the receiver at the same time. As shown in Fig. 3, the interference value of A_i from any two codes will differ depending on the groups where the codes are from. For mathematical convenience, we consider chips to be synchronous but with bit asynchronous interference in SIR and BER approximation. We assume that all users transmit data at an equal rate and with data duration $T_b = NT_c$ in a continuous fashion. Fig. 5 shows the received signal and the interference in a receiver. The undesired signal from the lth user from the mth group with relative chip delay τ_{il} to the ith user of the jth group is shown in Fig. 5(a) and (b), respectively. Here, $b_{l,m,n}$ is the previous or the present data bit of the lth user from the mth group for $n = -1$ or 0, which will be an interference to the desired present data bit of $b_{i,j,0}$. The interference will occur if any two chips of the ith and jth users at the same time are with a difference smaller than the group number N_{g}, i.e., $|F_{l,m}(t) - F_{i,j}(t)| < N_{\mathrm{g}}$. The interference from the lth user to the ith user can be written as

$$\begin{aligned} I_{\mathrm{il}} = &\sum_{d=0}^{\tau_{\mathrm{il}}-1} b_{l,m,-1} g\left(F_{i,j}(d), F_{l,m}(N-\tau_{\mathrm{il}}+d)\right) \\ &+ \sum_{d=\tau_{\mathrm{il}}}^{N-1} b_{l,m,0} g\left(F_{i,j}(d), F_{l,m}(d-\tau_{\mathrm{il}})\right) \end{aligned} \quad (10)$$

where

$$g(x,y) = \begin{cases} A_{|x-y|}, & \text{for } |x-y| < N_{\mathrm{g}} \\ 0, & \text{for } |x-y| \geq N_{\mathrm{g}} \end{cases} \quad (11)$$

where A_i is the normalized interference defined in the previous section and its value depends on the grating profile and the frequency interval. The relative delay τ_{il} is assumed uniformly distributed over integers $[0, N-1]$, and the data bits "0" and "1" are transmitted with equiprobability. We assume that there are N_i possible values of interference between any two sequences in the code set, and the probability of each interference can be denoted as $P_n(I_{\mathrm{il}} = I_n)$, where n is an integer over $[0, N_i - 1]$, and I_n is one of the possible interference values. The average variance of the multigroup codes can be derived as [25]

$$\sigma^2 = \sum_{m=0}^{N_i-1} \left[I_m - \left(\sum_{n=0}^{N_i-1} I_n \times P_n \right) \right]^2 P_m \quad (12)$$

where P_n denotes the average probability of having a cross-correlation value of $I_{\mathrm{il}} = I_n$ between any two sequences in the code set. If there are K simultaneous users, the total interference from the other $K-1$ users can be written as

$$I_t = (K-1)\sigma^2. \quad (13)$$

Therefore, the SIR can be derived directly as

$$\mathrm{SIR} = \frac{N^2}{I_t^2} = \frac{N^2}{(K-1)\sigma^2}. \quad (14)$$

D. Probability of Error

Here, we ignore other noise sources and consider only the MAI, which usually dominates the performance of a CDMA system. Using the Gaussian approximation for MAI

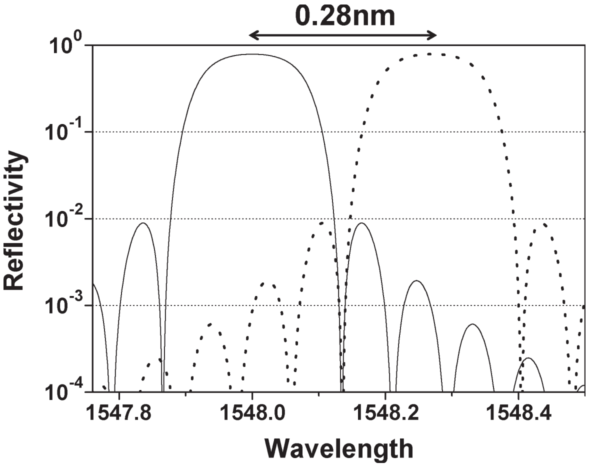

Fig. 6. Adjacent nonoverlapping Gaussian-apodization grating spectra of the same group, which we used for simulation. The first nulls are to be overlapped to increase the slot density.

and equiprobable data, the BER can be derived as [26]

$$P_{\mathrm{e}} = Q\left(\frac{\sqrt{\mathrm{SIR}}}{2}\right) \tag{15}$$

where

$$Q = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} \mathrm{e}^{-\frac{u^2}{2}} \, du. \tag{16}$$

Since we consider only the case of synchronous chips, the error probability will be the upper bound of the exact error probability [19]

$$P_{\mathrm{e}}(\text{exact}) \le P_{\mathrm{e}}\ (\text{chip-synchronous case}). \tag{17}$$

IV. NUMERICAL RESULTS AND DISCUSSIONS

A. Auto- and Cross-Correlation Functions

To estimate the performance of the proposed multigroup scheme, we calculate the auto- and cross-correlation functions for different number of groups. The total optical bandwidth is 7 nm, from 1551.86 to 1558.86 nm, and sliced to 25 nonoverlapping frequency slots with a bandwidth of 0.28 nm. Each user is assigned a unique code with length of $N = 12$, and each FBGA consists of 12 gratings corresponding to the code length. To reduce the sidelobe of the grating and increase the slot density, we use the Gaussian apodization for each grating, and the gratings are all with a peak coupling coefficient equal to 220 m^{-1}. The length of each grating is 10 mm, and the space between adjacent gratings is determined by the required chip rate and the tunability [19]. Since the sidelobe of each grating is 20 dB lower than the mainlobe, we will ignore its effect and consider the mainlobe only. The interval of the frequency slot Δf is selected allowing the first nulls of successive gratings to overlap for higher slot density, as shown in Fig. 6.

To evaluate the interference of different group number, 1 bit of all the 24 users is synchronously sent to the decoder of the first user, as shown in Fig. 7(a). The decoded outputs are shown in Fig. 7(b)–(d), where the interference is normalized to the power of the desired signal, which is located at the central peak. The pulses are of the Gaussian shape and are with a 3-dB pulsewidth of 0.2 chip duration.

In Fig. 7(b), it is found that the cross correlation is almost as high as the autocorrelation when all users are active. The system suffers serious interference, which will lose the correct detection window for the receiver and degrade the system performance. Fig. 7(c) shows the proposed system with the 2-group method. It is found that the cross-correlation function is reduced to only two-thirds of that in the conventional case. Increasing the number of groups, as shown in Fig. 7(d) and (e), where $N_{\mathrm{g}} = 6$ and 24, the cross correlation decreases to a level even lower than half of that in the conventional scheme. There is no apparent difference between the group number of 6 and 24. Since increasing the number of group requires stringent tenability and temperature controllability on the grating, the better group number that trades off between the signal performance and the system complexity might be 6 in this case.

B. Bit Error Rate (BER)

The simulation parameters, excepting that the bit synchronous is changed to the chip-synchronous assumption, are the same as the previous section. The average variance and the BERs for the proposed multigroup codes are derived from (12) and (15), respectively. Fig. 8 gives the probability of error versus the number of asynchronous simultaneous users with two different slot densities. Fig. 8(a) shows the case with a frequency interval of 0.28 nm, which allows the first nulls of the adjacent gratings to overlap. The performance is increasingly enhanced with the increasing of the group number. The proposed system can support up to four extra users for $N_{\mathrm{g}} = 2$ compared to the conventional one at a BER of 10^{-10}, and this increases to 8 when the group number N_{g} exceeds 6. Hence, the system capacity is clearly much improved. However, we found that the enhancement of the BER quickly saturates as the increasing group number. There is only a little improvement from group number of 6 to the group number of 24, but the required tuning and temperature control for group number of 24 is much stringent since the smallest spacing of two frequency slots is only 0.012 nm, and it is expected that slight variation of environmental parameters such as temperature, humidity, or stress will degrade the system seriously. It is very costly to maintain the performance of such a system. Thus, a tradeoff between the group number and the system reliability must be made, which will depend on the stability of the FBGA. In these simulation results, it seems that when the group number exceeds 6, the improvement of the BER is not so significant. Therefore, a group number with 6 rather than 24 would be a better choice in this example.

As described in Section II, since one additional frequency slot is required in our new scheme, we also simulate the case of the conventional scheme with one more slot in Fig. 8(a).

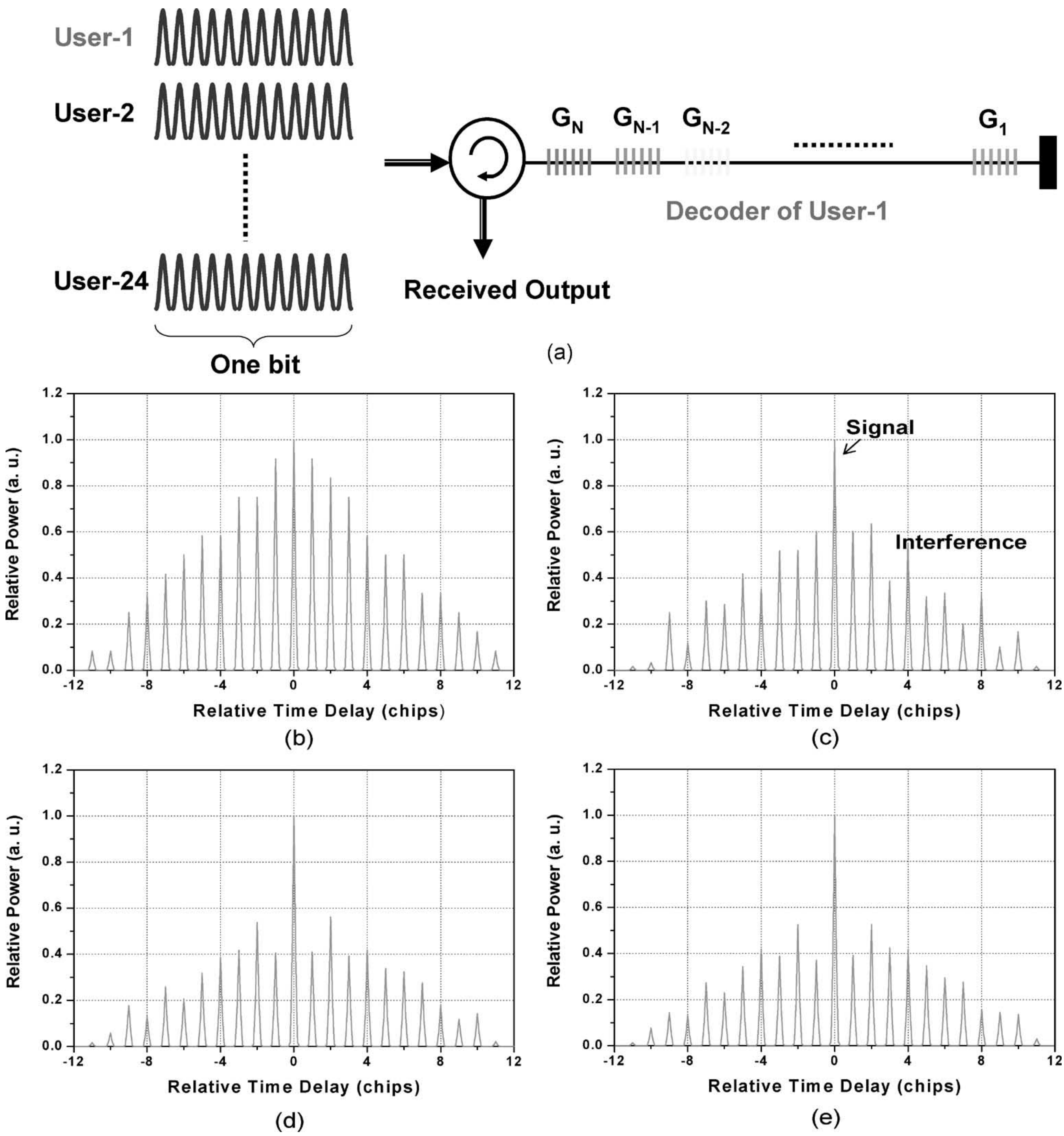

Fig. 7. (a) One bit of all the 24 users is synchronously sent to the decoder of the first user to evaluate the interference. (b)–(e) correspond to the group numbers of 1, 2, 6, and 24 for the code lengths of 12 from 25 available nonoverlapping frequency slots and 24 simultaneous users. The center peaks are of the autocorrelation and the side lobes are of the cross correlation.

However, it is not like that in our multigroup scheme; the improvement is very limited even with the one additional frequency slot.

Fig. 8(b) is the case with a frequency interval of 0.4 nm. Although the greater spacing of the frequency slots will decrease the slot number over the available bandwidth, the normalized interference A_i among the different groups becomes smaller. The frequency slots are now reduced to $q = 17$, and the code weight N is left unchanged. The group number of 1, 2, 4, 8, and 16 is shown in this figure, which indicates that the performance is getting better with the increasing number of groups. The saturation of the BER improvement is also observed.

Fig. 9 compares the performance of the two systems with different slot densities. With a smaller group number, the interference mainly results from the users of the same group.

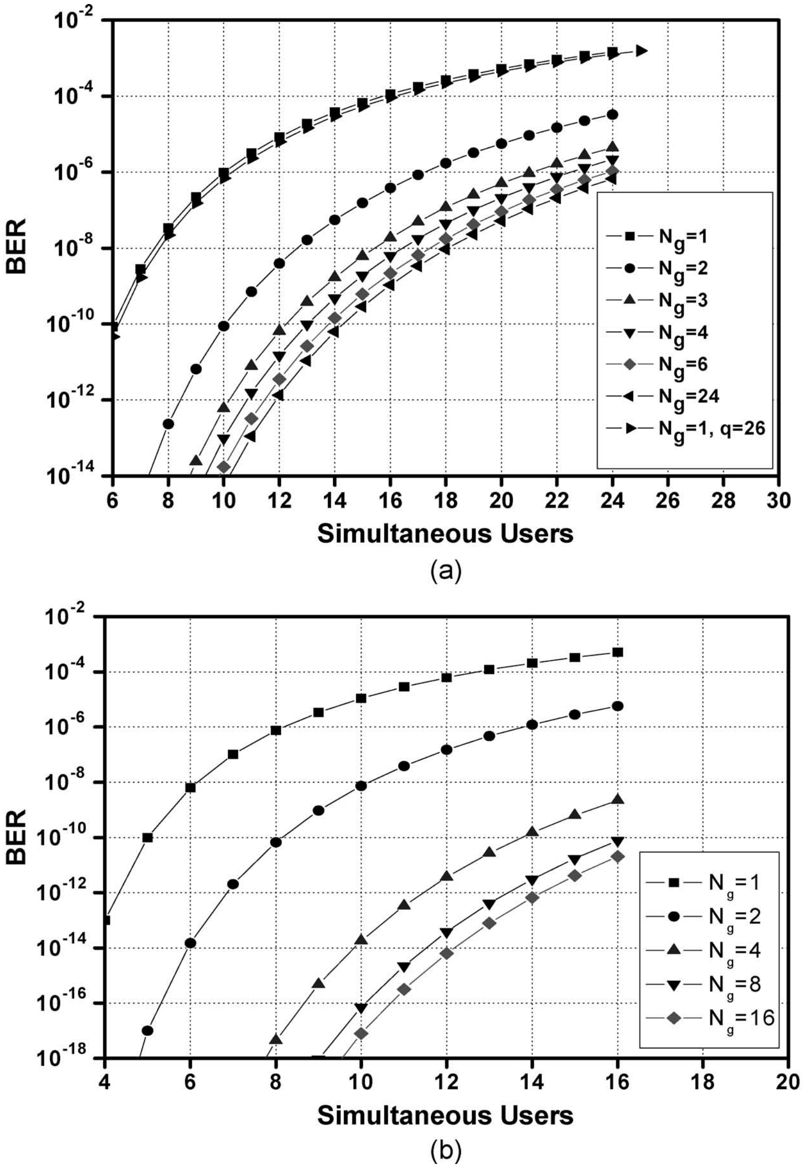

Fig. 8. (a) BER versus system simultaneous users over different numbers of groups with frequency slots of $q = 25$ and code weights of $N = 12$. The line with $q = 26$, $N = 12$ without grouping method is also shown for comparison. (b) BER versus system simultaneous users over different numbers of groups with frequency slots of $q = 17$ and code weights of $N = 12$.

This makes the system with lower slot density $q = 17$ have a higher probability to hit and to exhibit worse performance. When the group number increases, the dominant interference mainly comes from the users of different groups. That pushes the system with lower slot density $q = 17$ to perform better because of the smaller overlapping areas between the groups. It can be found that in the case of the maximum number of group, the system with $q = 17$ can support two more users than that with $q = 25$ at a BER of 10^{-12}. The impairment of a system with lower slot density is that there are fewer codes that can be used, which limits the maximum available users. In this example, there are 16 usable codes for slot number $q = 17$, while there are 24 usable codes for $q = 25$. However, the lower slot density also means the relaxation to the tuning and temperature controlling requirement and, therefore, low cost. Thus, for small size area, the lower slot density is preferred, and for larger area, the higher one could be a better choice. Therefore, the slot density and the group number should be carefully selected depending on the size of the network.

V. CONCLUSION

We propose a novel OFFH-CDMA system using a frequency-overlapping multigroup scheme to make more efficient use of the optical spectrum. Users of the different groups are assigned a different frequency allocation that is interleaved with each other. Reduced correlation among codes of different groups and more efficient use of the spectrum enhance the performance of the proposed OFFH-CDMA system. A new code set for this new scheme is developed and analyzed. With two additional constraints of this code set, performance with this code is much improved. The performance of the conventional scheme and the proposed scheme are compared in terms of the correlation function and the BER. With a Gaussian profile for

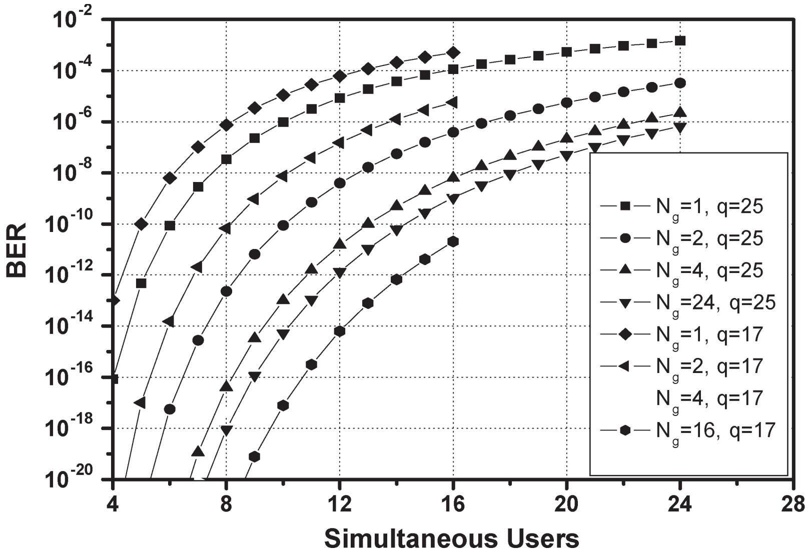

Fig. 9. BER comparisons for the above case, where the solid line is $(q, N) = (17, 12)$, and the dashed line is $(q, N) = (25, 12)$.

each grating, the performance is increasingly enhanced with the increase of the group number. However, it is not a good choice to select the maximum number of group due to the stringent fine tuning and necessary careful temperature control. Tradeoff must be made between the system performance and the hardware implementation. We also give the performance analysis with different frequency slot density. The system with lower slot density outperforms that with a higher slot density, in a larger group number, and lessens the requirement for tuning accuracy and temperature control. The corresponding shortcoming is the fewer usable codes in the system. Which one is better depends on the size and the cost of the network.

Another important issue is that in our simulation, the used profile of a grating is approximately Gaussian. If a flattop profile grating has been used in our proposed scheme for better power efficiency, the interference is the same as the conventional scheme, and no gain is obtained with this scheme. However, with a Gaussian or other nonflattop grating, the interference can be largely reduced at a price of lower power efficiency. Hence, an appropriate profile should be selected under the considerations of both the power efficiency and the MAI.

REFERENCES

[1] E. Marom and O. G. Ramer, “Encoding–decoding optical fiber network,” *Electron. Lett.*, vol. 14, no. 3, pp. 48–49, 1978.

[2] P. Prucnal, M. Santoto, and T. Fan, “Spread spectrum fiber optic local area network using optical processing,” *J. Lightw. Technol.*, vol. LT-4, no. 5, pp. 307–405, May 1986.

[3] W. Kwong and P. Prucnal, “Synchronous CDMA demonstration for fiber optic networks with optical processing,” *Electron. Lett.*, vol. 26, no. 24, pp. 2219–2220, Nov. 1990.

[4] W. C. Kwong, P. Perrier, and P. R. Prucnal, “Performance comparisons of asynchronous and synchronous code-division multiple-access techniques for fiber-optic local area networks,” *IEEE Trans. Commun.*, vol. 39, no. 11, pp. 1625–1634, Nov. 1991.

[5] A. S. Holmes and R. Syms, “Switchable all-optical encoding and decoding using optical fiber lattices,” *Opt. Commun.*, vol. 86, no. 1, pp. 25–28, 1991.

[6] ——, “All optical CDMA using ‘quasi-prime’ codes,” *J. Lightw. Technol.*, vol. 10, no. 2, pp. 279–286, Feb. 1992.

[7] J. G. Zhang and G. Picchi, “Tunable prime-code encoder/decoder for all optical CDMA applications,” *Electron. Lett.*, vol. 29, no. 13, pp. 1211–1212, Jun. 1993.

[8] J. G. Zhang and W. C. Kwong, “Novel designs of programmable all-optical synchronous code-division multiple-access encoders and decoders,” *Opt. Eng.*, vol. 34, no. 7, pp. 2109–2114, Jul. 1995.

[9] L. Tancevski and I. Andonovic, “Block multiplexing codes for incoherent optical ladder network correlators,” *IEEE Photon. Technol. Lett.*, vol. 6, no. 2, pp. 309–311, Feb. 1994.

[10] P. C. Teh, P. Petropoulos, M. Ibsen, and D. J. Richardson, “A comparative study of the performance of seven- and 63-chip optical code-division multiple-access encoders and decoders based on superstructured fiber Bragg gratings,” *J. Lightw. Technol.*, vol. 19, no. 9, pp. 1352–1365, Sep. 2001.

[11] P. C. Teh, M. Ibsen, J. H. Lee, P. Petropoulos, and D. J. Richardson, “Demonstration of a four channel WDM/OCDMA system using 255-chip 320-Gchip/s quarternary phase coding gratins,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 2, pp. 227–229, Feb. 2002.

[12] J. H. Lee, P. C. Teh, P. Petropoulos, M. Ibsen, and D. J. Richardson, “A grating-based OCDMA coding-decoding system incorporating a nonlinear optical loop mirror for improved code recognition and noise reduction,” *J. Lightw. Technol.*, vol. 20, no. 1, pp. 36–46, Jan. 2002.

[13] J. A. Salehi, A. M. Weiner, and J. P. Heritage, “Coherent ultrashort light pulse code-division multiple access communication,” *J. Lightw. Technol.*, vol. 8, no. 3, pp. 478–491, Mar. 1990.

[14] D. J. Hajela and J. A. Salehi, “Limits to the encoding and bounds on the performance of coherent ultrashort light pulse code-division multiple access,” *IEEE Trans. Commun.*, vol. 40, no. 2, pp. 325–336, Feb. 1992.

[15] D. Zaccarin and M. Kavehrad, “An optical CDMA system based on spectral encoding of LED,” *IEEE Photon. Technol. Lett.*, vol. 5, no. 4, pp. 479–482, Apr. 1993.

[16] A. G. Jepsen, A. E. Johnson, E. S. Maniloff, T. W. Mossberg, M. J. Munroe, and J. N. Sweetser, “Fibre Bragg grating based spectral encoder/decoder for lightwave CDMA,” *Electron. Lett.*, vol. 35, no. 13, pp. 1096–1097, Jun. 1999.

[17] K. Kiasaleh, “Fiber optic frequency hopping multiple access communication system,” *IEEE Photon. Technol. Lett.*, vol. 3, no. 2, pp. 173–175, Feb. 1991.

[18] ——, “Performance of packet-swithed fiber-optic frequency-hopping multiple-access networks,” *IEEE Trans. Commun.*, vol. 43, no. 7, pp. 2241–2253, Jul. 1995.

[19] H. Fathallah, L. Rusch, and S. Larochelle, “Passive optical fast frequency-hop CDMA communications system,” *J. Lightw. Technol.*, vol. 17, no. 3, pp. 397–405, Mar. 1999.

[20] H. Fathallah and L. Rusch, “Robust optical FFH-CDMA communications: Coding in place of frequency and temperature control,” *J. Lightw. Technol.*, vol. 17, no. 8, pp. 1284–1293, Aug. 1999.

[21] E. Inaty, H. M. H. Shalaby, and P. Fortier, "A new transmitter–receiver architecture for noncoherent multirate OFFH-CDMA system with fixed optimal detection threshold," *J. Lightw. Technol.*, vol. 20, no. 11, pp. 1885–1894, Nov. 2002.

[22] E. Inaty, H. M. H. Shalaby, P. Fortier, and L. Rusch, "Multirate optical fast frequency hopping CDMA system using power control," *J. Lightw. Technol.*, vol. 20, no. 2, pp. 166–177, Feb. 2002.

[23] A. A. Shaar and P. A. Davies, "A survey of one-coincidence sequences for frequency hopped spread spectrum systems," *Proc. Inst. Elect. Eng. Pt. F—Commun., Radar Signal Process.*, vol. 131, no. 7, pp. 719–724, Dec. 1984.

[24] L. Bin, "One coincidence sequences with specified distance between adjacent symbols of frequency-hopping multiple-access," *IEEE Trans. Commun.*, vol. 45, no. 4, pp. 408–410, Apr. 1997.

[25] G. C. Yang and W. C. Kwong, "Performance analysis of optical CDMA with prime codes," *Electron. Lett.*, vol. 31, no. 7, pp. 569–570, Mar. 1995.

[26] J. Salehi, "Code division multiple-access techniques in optical fiber networks—Part 2: Systems performance analysis," *IEEE Trans. Commun.*, vol. 37, no. 8, pp. 834–842, Aug. 1989.

Wei-Ren Peng was born in Hsinchu, Taiwan, R.O.C., on 1978. He received the B.S. degree in electrical engineering from the National Taiwan University, Taiwan, in 2001, the M.S. degree in electro-optical engineering from the National Chiao-Tung University, Hsinchu, Taiwan, in 2003, and is currently working toward the Ph.D. degree at the Institute of Electro-Optical Engineering, National Chiao-Tung University.

His research interests are optical code-division multiple-access network and optical modulation formats.

Wen-Piao Lin (S'01–M'02) was born in Changhua, Taiwan, R.O.C., in 1957. He received the B.S.E.E. and M.S.E.E. degrees from National Taiwan Institute of Technology, Taipei, Taiwan, in 1982 and 1985, respectively, and the Ph.D. degree in Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan, in 2002.

From 1985 to 1987, he joined the Hua-Eng Company, Kaohsiung, Taiwan, where he engaged in research in the area of optical-fiber subscriber loops. In 2003, he joined the Faculty of Chang Gung University, Taoyunan, Taiwan, where he is currently an Associate Professor. At present, he is interested in the broadband highway fiber-wireless networks.

Sien Chi received the B.S.E.E. degree from National Taiwan University, Taipei, Taiwan, R.O.C., and the M.S.E.E. degree from National Chiao-Tung University, Hsinchu, Taiwan, in 1959 and 1961, respectively. He received the Ph.D. degree in electro-physics from Polytechnic Institute, Brooklyn, NY, in 1971.

From 1971 to 2004, he was a Professor at National Chiao-Tung University. He is currently a Chair Professor at Yuan-Ze University, Chung Li, Taiwan. His research interests are optical-fiber communications, optical solitons, optical modulation format, and optical-fiber amplifiers.

Dr. Chi is a Fellow of both the Optical Society of America (OSA) and the Photonics Society of Chinese Americans (PSCA). He was the Symposium Chair of the International Symposium of Optoelectronics in Computers, Communications, and Control, in 1992, which was coorganized by the National Chiao-Tung University and The International Society for Optical Engineers (SPIE). Since 1996, he has been the Chair Professor of the Foundation for Advancement of Outstanding Scholarship. From 1998 to 2001, he was the Vice President of the National Chiao-Tung University.