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Optical CDMA system with the least multiple access interference under arbitrary restrictions

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Abstract

The most important issue in asynchronous optical code division multiple-access (CDMA) systems is the multiple access interference (MAI), which is caused by the non-ideal orthogonal property of optical codes and which is the main factor of the bit error. In this paper, we propose and examine an extremely versatile optical code, the adaptive resonance code (ARC), which has the least MAI under arbitrary restrictions arising from designing optical CDMA systems. The analytical results show that ARC has near-ideal MAI and that the available number of nodes in a system is doubled without changing the coding scheme and/or physical structure of the system at the cost of little performance degradation. In the traditional method of implementing an optical CDMA system, components such as optical sources and encoders/decoders are designed after choosing an optical code. When ARC is used, it is also possible that components are first designed with their own specialties and then an optimal code set for the components is generated.

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Keywords: Optical communications; Optical code division multiple-access; Optical code; Multiple access interference

1. Introduction

An optical code division multiple-access (CDMA) system as shown in Fig. 1 is expected to be an attractive substitute for the future optical subscriber network due to its advantages, which include the large number of subscribers in shared media, a high level of security and simple architecture. As the bursty traffic increases in the network, the optical CDMA system with an asynchronous scheme becomes one of the best solutions [1].

There have been proposed various asynchronous optical CDMA systems that utilize one-dimensional (1-D) codes such as time-spreading schemes [2] or two-dimensional (2-D) codes such as time-wavelength hybrid (TWH) schemes [3–5]. Especially, the TWH schemes mainly considered in this paper attract increasing research interests due to their good bit error rate (BER) performance and greatly increased cardinality.

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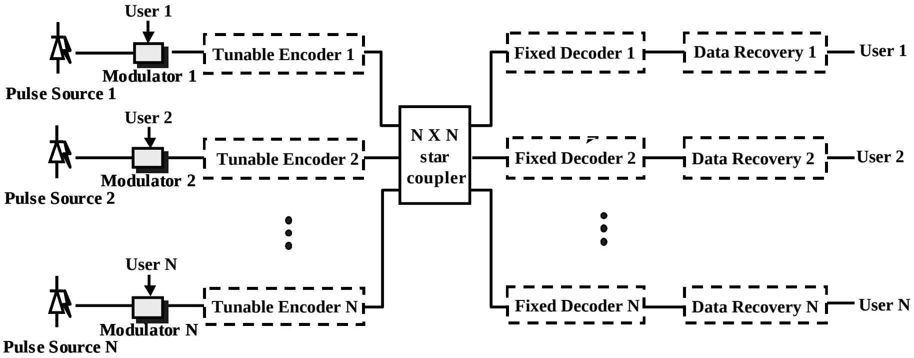

Fig. 1. An optical CDMA system for LAN applications.

The two most important issues when designing an asynchronous optical CDMA system are the implementation of reasonable tunable encoders to generate optical codes such as those proposed in [2–5] and mitigation of the multiple access interference (MAI), which is caused by the non-ideal orthogonal property of optical codes (non-zero cross-correlation values in unipolar code set). Although all sources of physical noise including shot, thermal and beat noise affect on system performance [6,7], the MAI is the main factor of the bit error and hence must be kept as small as possible. These two issues are mutually correlated, therefore the scheme to implement optical tunable encoders/decoders should also be considered when the optical code is designed; i.e., some restrictions on generating the optical code set lead to easy implementation of the encoders/decoders.

However, the previous works [2–5] on the optical code sets for optical CDMA systems have concentrated on the properties as signature sequences without considering the easy implementation of encoders/decoders. These properties include autocorrelation, cross-correlation and cardinality of code sets. Therefore, the implementation of reasonable tunable encoders/decoders becomes the most difficult problem of the realization of optical CDMA systems. In order to unravel the problem, several tunable encoder/decoder schemes to generate specific code sets have been presented [8–10].

In this paper, we propose and examine an extremely versatile optical code, an adaptive resonance code (ARC), with a very high security level. The code has near-optimal MAI under arbitrary restrictions arising from designing optical CDMA systems such as code length, the number of wavelengths and pulses in a codeword and the desired number of distinctive sequences. An optimal optical code set for the previously designed components, including encoders/decoders and optical sources with their own specialties like those proposed in [8–11], can be implemented. Therefore, ARC allows network designers to implement an optimal optical CDMA system flexibly. In addition, by using the proposed code generation technique, the available number of nodes in a network can be increased without changing the coding scheme and/or the physical structure of system at the cost of very little performance degradation.

2. Adaptive resonance code

In an optical CDMA system for LAN applications, the most important issues are MAI mitigation, the maximum number of supportable nodes, the level of security, the implementation of a tunable encoder and a fixed decoder and a short-pulse laser (Fig. 1). In order to select the most profitable scheme for a real optical CDMA system, all of the above issues are reflected on but in most existing code families, the auto- and cross-correlation properties (or MAIs) have just been considered as the performance measure of the code.

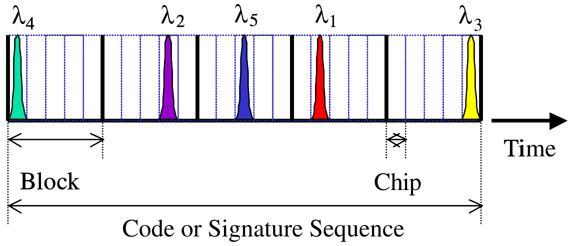

Fig. 2. An example of single-pulse-per-row/column codes, in which a codeword consists of several blocks and each block has a pulse having different wavelength and chip position (Table 1).

If a code set is generated under some restrictions, the implementation of a tunable encoder will be easier. For example, if a codeword consists of several blocks and each block has a pulse with a different wavelength and chip position (single-pulse-per-row/column or sppr/c codes, Fig. 2), fixed delay lines (FDLs) can be used to delay pulses to desired blocks so that the tunable delay lines (TDLs) used in the tunable encoder can operate within the range of a corresponding block, thus this can reduce the number of required devices such as switches and FDLs [8]. The prime-hop [3] and eqc-prime codes [5] are good examples of sppr/c codes.

The bit rate r_b of user data and the number of nodes in a network may be decided by commercial policy. Once the bit rate r_b has fixed, the chip rate r_c of the encoded signals is determined by the state-of-the-art technology to generate a short pulse or by other commercial reasons. As a result, the code length F is given by $F = r_c/r_b$. Now, the ARC with near-optimal MAI satisfying the above-mentioned factors (sppr/c property, bit rate and chip rate) can be generated.

In this section, in order to explain the principle of generating ARC we consider the asynchronous optical CDMA system utilizing a TWH 2-D unipolar optical code, in which every pulse of a codeword is encoded in wavelength and in time domain. In the code set, S ones in a codeword and H wavelengths are used.

In the optical CDMA system, many asynchronous users occupy the same channel simultaneously. A desired user's receiver must be able to extract its signature sequence in the presence of other users' signature sequences. Therefore, a code set as a signature sequence for the optical CDMA system should have a needle shape of autocorrelation function and cross-correlation values as small as possible.

In a TWH 2-D code set, the maximum autocorrelation sidelobe of 0 can be easily achieved if the number of wavelengths is more than or equal to the weight. However, the obtainable smallest maximum cross-correlation value between two different unipolar codes is 1. Consequently, the MAI, which is the heap of cross-correlations, is added to the original signal and causes the bit error when data "0" is sent from the transmitter.

A TWH 2-D code set $\boldsymbol{C}$ is a collection of N binary (0,1) $F \times H$ matrices with Hamming weight S, which has the following properties: When the bit time T_b and the chip time is T_c, the code length F is T_b/T_c. The autocorrelation $Z_{x,x}(l)$ for a codeword $\boldsymbol{X} \in \boldsymbol{C}$ is defined as follows:

$$Z_{x,x}(l) = \sum_{m=0}^{H-1} \sum_{n=0}^{F-1} x_{m,n} x_{m,\lfloor n+l \rfloor_{\mathrm{mod}F}}, \tag{1}$$

where l indicates the amount of chip difference between two codes, $x_{m,n} \in \{0,1\}$ is an element of matrix $\boldsymbol{X}$, and $\lfloor \circ \rfloor_{\mathrm{mod}F}$ denotes the modulo F operation. The cross-correlation $Z_{x,x}(l)$ of two codes satisfies

$$Z_{x,x}(l) \begin{cases} = S, & \text{if } l = 0, \\ \leqslant \lambda_a, & \text{if } 1 \leqslant l \leqslant (F-1), \end{cases} \tag{2}$$

where λ_a is the maximum autocorrelation sidelobe.

The cross-correlation $Z_{x,y}(l)$ of two codes $\boldsymbol{X}$ and $\boldsymbol{Y}$ is defined as follows:

$$Z_{x,y}(l) = \sum_{m=0}^{H} \sum_{n=0}^{F-1} x_{m,n} y_{m,\lfloor n+l \rfloor_{\mathrm{mod}F}}, \tag{3}$$

where $x_{m,n}$ and $y_{m,n} \in \{0,1\}$ are an element of matrix $\boldsymbol{X}$ and $\boldsymbol{Y}$, respectively. $Z_{x,y}(l)$ satisfies

$$Z_{x,y}(l) \leqslant \lambda_c \quad \text{for } 0 \leqslant l \leqslant (F-1), \tag{4}$$

where λ_c is the maximum cross-correlation value.

2.1. Code generation procedure

The procedure of generating TWH 2-D ARC is shown below:

1. Set restrictions such as
   - the number of desired maximum nodes in a network or cardinality N,
   - the number of wavelengths H in a code set,
   - the number of pulses or Hamming weight S in a codeword,
   - whether signature sequences or codes consist of blocks or not,
   - the number of pulses contained in a block and the number of blocks if needed,
   - code length F,
   - auto- and cross-correlation constraints (λ_a and λ_c) if needed.
2. Generate N codes randomly satisfying above restrictions.
3. Calculate the MAI at each node by $N-1$ other users. The MAI at ith node is defined as follows:

$$\begin{aligned}\mathrm{MAI}_i &= \sum_{j=1,j\neq i}^{N} \max_k \{Z_{i,j}(k)\} \\ &\quad \text{for } 0 \leqslant k \leqslant (F-1), \\ &\quad \text{for } 0 \leqslant i,j \leqslant (N-1),\end{aligned} \tag{5}$$

   where $\max_k\{\circ\}$ is the maximum value in all k and the worst case was assumed to get the upper-bound of the MAIs.
4. Choose a node i^* for code regeneration.
   (a) Select a node with the maximum MAI with probability γ, which is a node selection factor.
   (b) If i^* is not selected, choose a node with the next maximum MAI with probability γ.
   (c) If i^* is not selected, repeat **b** until i^* is determined.
5. Regenerate the code for node i^*.
6. Calculate new MAI_{i^*} at the i^*th node.
7. If the new MAI_{i^*} is less than or equal to old MAI_i, accept the regenerated codeword and go to the next step. Otherwise, accept the code with probability α, which is defined as

$$\alpha = ((\mathrm{newMAI} - \mathrm{oldMAI})\beta)^{-1}, \tag{6}$$

   where β is an accepting factor between 0 and 1 and determines how much the increase of MAI influences the acceptance.
8. Check ending criteria such as whether the total MAI is less than a predetermined value, or whether the overall MAIs have not changed for pre-defined iterations. If the criteria are satisfied, the procedure will be finished, otherwise, go to step (3).

The node selection factor γ, the accepting factor β, the regenerating method of the i^*th code in step (5) and the ending criteria can be chosen according to the user's discretion. The node selection factor γ and the accepting factor β affect the convergent speed to the optimal point and the possible minimum total MAI. In other words, the factors (γ and β) determine whether the final total MAI of the generated code set would drop into global minima or local minima. The total MAI is defined as the sum of all MAIs.

$$\text{Total MAI} = \sum_{i=1}^{N} \mathrm{MAI}_i. \tag{7}$$

In order to regenerate the code with the maximum MAI in step (5), several methods, including the Genetic Algorithm, stimulated annealing and random selection schemes, can be used.

2.2. Generated ARCs

As the number of iterations was increased, the total MAI decreased as shown in Fig. 3, which illustrates the total MAI trace when a code set with $S = H = 5$, $F = 45$ and $N = 80$ was generated where the total MAIs at iteration of 0, 5000 and 25,800 were 7752, 6840 and 6672, respectively, and $\gamma = 0.73$ and $\beta = 0.6$ were used.

An example of ARC generated under some restrictions for $S = 5$, $H = 5$, $F = 25$ and $N = 16$ is

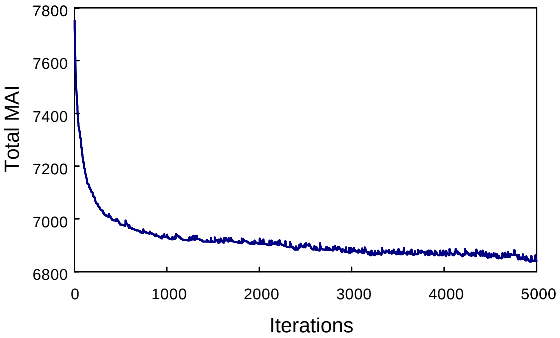

Fig. 3. MAI trace as the iteration for $S = H = 5$, $F = 45$ and $N = 80$.

Table 1
An example of the ARC for $S = H = 5$, $F = 25$ and $N = 16$

Code no.	Generated signature sequence
0	40000 00020 00500 01000 00003
1	10000 00020 04000 00005 00300
2	50000 00100 00020 03000 00004
3	40000 01000 00020 00003 00500
4	40000 00005 00100 02000 00030
5	50000 00004 03000 00020 00100
6	40000 00003 01000 00500 00020
7	10000 04000 00300 00020 00005
8	10000 00300 00005 04000 00020
9	40000 00500 00003 00020 01000
10	50000 03000 00100 00004 00020
11	40000 00030 02000 00100 00005
12	40000 00100 00030 00005 02000
13	10000 00005 00020 00300 04000
14	50000 00020 00004 00100 03000
15	40000 02000 00005 00030 00100

The total MAI of generated code set is 240 ($\lambda_c = 1$) and the number of iterations is 10657.

shown in Table 1. When the code set was generated, $\gamma = 0.7$, $\beta = 0.9$ were used. In the spreading pattern, the number n except zero means the pulse with the nth available wavelength and '0' denotes that the chip contains no pulses. The first code of Table 1 is illustrated in Fig. 2.

In this example, a codeword consists of 5 blocks and each block contains one pulse having the different chip position in each block (sppr/c code). This structural property of codes has merits when a tunable encoder is implemented. The tuning range of the encoder can be reduced so that the complexity and cost is decreased [8].

The final total MAI of the generated code set at the iteration of 10,657 was 240 corresponding to the ideal cross-correlation property, which means that the maximum cross-correlation value of the generated ARC is 1 ($\lambda_c = 1$). Whereas, when a code set without the sppr/c property was generated, the total MAI of 240 could be obtained at the iteration of 215.

The maximum autocorrelation side-lobe of ARC in Table 1 is zero ($\lambda_a = 0$) since the number of pulses in a codeword is the same as the number of wavelengths; hence, all pulses in a codeword have different wavelengths.

The cardinality of 16 was the maximum value for the code set with the ideal MAI and sppr/c property for $S = 5$, $H = 5$ and $F = 25$. In case $N = 17$, the final total MAI was 282 while the ideal total MAI was 272.

2.3. *MAI comparison*

In order to examine the superiority of ARC over existing codes, the total MAI and peak autocorrelation sidelobe of the generated ARC were compared with various existing TWH codes: prime-hop code [3], multi-wavelength optical orthogonal code (MWOOC) [4], eqc-prime code [5] and CDMA + WDMA scheme [12] (Table 2). An ARC set with $S = 3$, $H = 7$, $F = 7$ and $N = 56$ was generated to compare with MWOOC and for $S = 5$ and $H = 5$, several code sets with different values of F and N were used to be compared with the other codes.

The values of S, H, F and N were matched to those of compared codes since the prime-hop and eqc-prime algorithm can be used to generate codes with specific code-lengths and weights while the ARC is possible for any S, H, F and N.

Table 2
MAI comparison of various TWH code families in worst case for $S = 5$ and $H = 5$: total MAI (the maximum autocorrelation side-lobes)

Code family	$F = 25$ $N = 5$	$F = 25$ $N = 20$	$F = 25$ $N = 46$	$F = 45$ $N = 80$	$S = 3$, $H = 7$ $F = 7$, $N = 56$
ARC	20 (0)	386 (0)	2292 (0)	6672 (0)	1798 (0)
OW	20 (1)	760 (2)	6210 (3)	12640 (2)	Imp
PH	20 (0)	380 (0)	Imp	Imp	Imp
EP	Imp	Imp	Imp	7200 (0)	Imp
MW	Imp	Imp	Imp	Imp	2646 (0)
OC	ARC	PH	ARC	ARC	ARC

Imp: impossible, OW: OOC + WDMA, PH: prime-hop, EP: eqc-prime, MW: MWOOC, OC: optimal code.

For example, the code length of 25 and the cardinality of 20 were selected for comparing with prime-hop code since the code length and cardinality of prime-hop code set are given by $F = S^2$ and $N = S^*(H-1)$, respectively, and the weight should be equal to the number of wavelengths. The prime-hop code has $\lambda_c = 1$, which is the obtainable minimum value in the unipolar optical codes in the case that the weight of a code is equal to the number of wavelengths used [3].

For the eqc-prime code set, the code length and the cardinality are given by $F = S^*(2S-1)$ and $N = H^*(S-1)^*(H-1)$, respectively, and the code set has $\lambda_c = 2$ [5]. The weight S and the number of wavelengths H must be prime numbers for the prime-hop and eqc-prime codes while S and H may be arbitrary integers for the ARC.

In the code set with $\lambda_c = 1$ generated by the combined method of the OOC and WDMA (OOC + WDMA code), the cardinality is given by

$$N \leqslant H\left\lceil \frac{F}{S(S-1)} \right\rceil, \tag{8}$$

where $\lceil x \rceil$ denotes the largest integer below x. The maximum cardinalities of the code set is therefore 5 for $S = 5$, $H = 5$ and $F = 25$ [12].

In MWOOC families, the code length, the number of wavelength and the cardinality are given by $F = S(S-1)t + 1$, $H = F$ and $N = F(F+1)t$ respectively, where t is an integer and it was set to 1 in this paper [4].

Table 1 shows that ARCs have smaller MAI values than other codes except code with $N = 20$, where the prime-hop code has the ideal properties: $\lambda_a = 0$ and $\lambda_c = 1$. The total MAI of the prime-hop code was 380 and the total MAI of ARC was 386. We believe that this slightly larger MAI value of ARC can be reduced by doing more iteration or by selecting other γ and β although the influence of the MAI increase on the BER performance is negligible as shown in Fig. 5.

3. Implementation considerations

In a TWH 2-D optical CDMA system utilizing the ARC for LAN applications, fundamental devices are multi-wavelength or broadband sources to generate a short pulse train, tunable encoders to generate a signature sequence of the desired node, fixed decoders to receive the data destined only to themselves and detectors to recover the user data from the decoded signal (e.g., Fig. 1). An optical hard-limiter (OHL) used in front of the decoder has also been considered in order to reduce the MAI at the receiver site. In this section, the requirements of each component for a TWH optical CDMA system are examined briefly.

Optical sources for TWH 2-D optical CDMA systems have to generate a high power, short pulse train (over few watts of peak power and less than 100 ps of pulse-width) with multiple wavelengths or broadband spectrum at a relatively low repetition rate (less than 155 MHz). The pulse width corresponds to the chip rate, which is much higher than the data rate since an encoded data sequence typically consists of a lot of chips and the repetition rate of the short pulse from the source depends on the data rate. The cascaded distributed-feedback (DFB) fiber laser with a high-speed modulator and a passively mode-locked fiber laser such as a figure-eight fiber laser (F8L) are potential candidates [11].

The OHL, which can clip the signal power exceeding the pre-set limit, is optional for the mitigation of MAI in a system with many nodes. The OHL for the TWH system should be able to chop the input short pulse with multiple wavelengths and have a very wide dynamic range (in the worst case, up to 30 dB). A non-linear optical loop mirror (NOLM) with a non-linear device in the loop, an optical thyristor, or multiple wavelength converters utilizing cross-phase modulation can be employed as an OHL.

In the consideration of a tunable encoder, a cost-effective and compact spreading scheme in time-wavelength domain, simple programmable operation, and the matched delay and wavelength operation with the decoder are needed. Fig. 4 shows three examples of the tunable encoders. The first scheme uses tunable fiber Bragg gratings (FBGs), whose center wavelength can be varied over 40 nm by using the state-of-the-art technology and tunable delay lines (TDLs), which are complicated to implement and potentially cause the power loss. The second scheme utilizes mirrors,

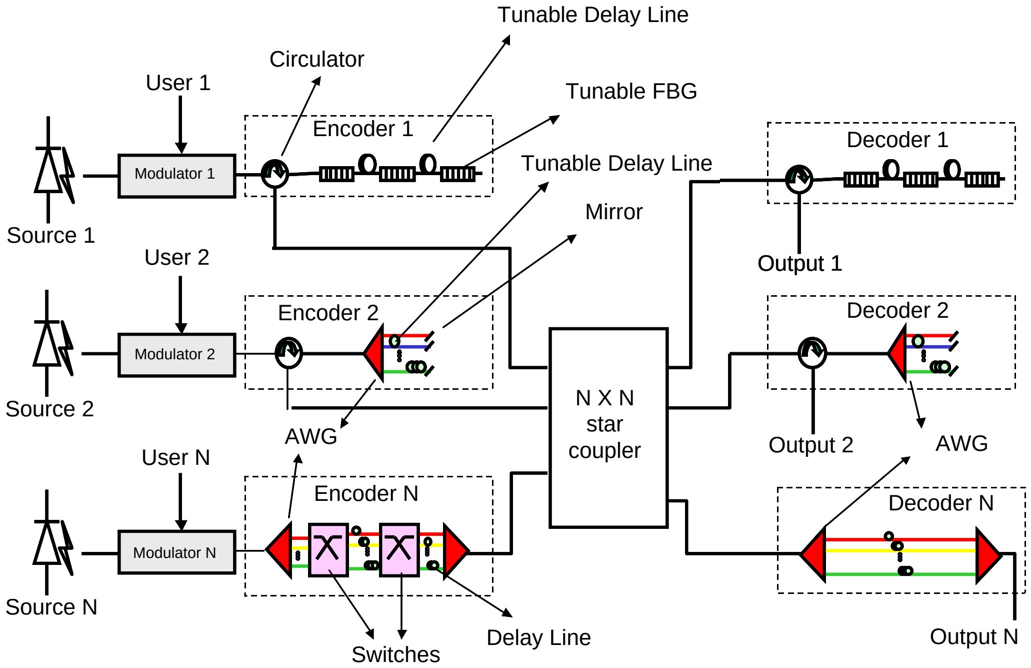

Fig. 4. An example of the TWH 2-D optical CDMA system.

TDLs and an arrayed waveguide grating (AWG) instead of the tunable FBGs, but it requires the TDLs with wider tuning range than those in the first scheme. The implementation of mirrors with small loss is another problem in this scheme. The final scheme employs an AWG, switches and fixed delay lines (FDLs) instead of the TDLs so that it gives lower loss. In addition, this scheme employs two sets of a switch and several FDLs to reduce the number of required components [8]. In the tunable encoder, the tuning speed is not an important factor since users change the target sequence only when they want to communicate with other users. Therefore, the small loss and the low cross-talk are more important factors to improve the performance.

A simple and low cost correlation technique matched with encoder is required for the decoder. As shown in Fig. 4, cascaded FBGs with FDLs, an AWG with FDLs and mirrors and two AWGs connected by FDLs are good choices for this purpose. The decoder is typically not required to be tunable.

If we use the ARC as a signature sequence, we may design all of the required devices first and then generate the optimal optical code set for the designed devices. It is also possible to increase the number of signature sequences in existing networks that do not have available signature sequences enough to support all required nodes. The ART therefore provides a system designer a flexible method to implement an optical CDMA system.

4. Performance analysis

4.1. System description

The asynchronous optical CDMA system considered here employs a TWH 2-D unipolar ARC. The system utilizes a star topology with encoders/decoders as shown in Fig. 1, in which all users send pulses with the same power level. This configuration is generally considered for LAN applications. In this analysis, we assume that the system performance is dominated by MAI. In order to get the upper bounds on BER, we assume the perfect chip synchronization as the worst case, in which two pulses or chips from two different transmitters are completely coincided [13].

When K users are transmitting signals simultaneously, $K-1$ users contribute to MAI. When a user transmits a "1" data, the encoder generates a code sequence of F chips, where only S of these are "1" and others are "0". Each pulse has different wavelength being one of H wavelengths. When a "0" data bit is sent, no pulses are generated.

At the receiver site, a photo-detector, placed after an optical correlator (decoder), converts decoded optical signals into electrical signals and a threshold detector recovers the original data from the sampled data of the integrated signal. The threshold detector estimates the sent data as one when the input signal exceeds a threshold level and otherwise it concludes the data to be zero.

4.2. BER analysis

Because we assumed that the system performance is dominated by the MAI, the bit error occurs only when the interferences are accumulated on the original "zero-data" signals and the magnitude of total interference is greater than the threshold level of the detector.

When K users are transmitting simultaneously, the MAI at a given receiver is the superposition of $K-1$ different cross-correlation functions. If the $K-1$ interferers are uncorrelated, the mean and variance of the MAI are equal to the sum of the means and variances of the $K-1$ cross-correlation functions, respectively.

When a periodic correlation process is performed between a pair of codes in optical processing from a constant weight code set with the constant numbers (weight S, the number of wavelengths H and code length N), the mean of cross-correlation values of 2-D codes can be derived from the following equation for 1-D codes derived by Lee and Green [14].

$$\mu_{1\mathrm{D}} = \frac{S^2}{2N}. \tag{9}$$

In the 1-D codes, only one wavelength is used to encode the information.

In Eq. (9), an equiprobable system was assumed. Note that only weight and code length determine the mean of cross-correlation values in any 1-D code set. Eq. (9) was derived from the coincidence probability of the 1s between two sequences. In 2-D code, the coincidence probability is decreased by the multiple wavelengths. The average value for 2-D codes is therefore given by

$$\mu_{2\mathrm{D}} = \frac{S^2}{2NH}. \tag{10}$$

The average values estimated in our simulation agreed with those calculated from Eq. (10).

Considering other users' interference to be the dominant source of noise in the system, the signal-to-noise ratio (SNR) is represented as the ratio of square of the difference between the peak of the autocorrelation function and the mean of MAI to the variance of amplitude of MAI,

$$\mathrm{SNR}_{\mathrm{optical}} = \frac{S^2 - (K-1)\mu_{2\mathrm{D}}}{\sigma^2 (K-1)}. \tag{11}$$

The ARC is not generated by mathematical equation but iterative algorithm; therefore, the variance of the cross-correlation for ARC cannot be derived mathematically but is only obtained via a simulation using generated code sets or by estimating all possible cross-correlation values between two generated sequences.

Assuming the chip synchronization among received signals as the worst case, the SNR for each code can be obtained by estimating the average variance of the cross-correlation. BER for the optical CDMA system is given by

$$\mathrm{BER} = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{\mathrm{SNR}}}^{\infty} \exp\left(\frac{-v^2}{2}\right) \mathrm{d}v. \tag{12}$$

4.3. Results

The BER performance of the generated ARC was compared with existing TWH codes: prime-hop code [3] and eqc-prime code [5]. The values for S, H and F were selected for compared code sets since the prime-hop and eqc-prime algorithm can be used to generate codes with specific S, H and F while the ART can generate an arbitrary code.

The mean value of cross-correlation required to obtain the error probability from Eq. (12) was calculated using Eq. (10). Assuming the chip synchronization among received signals as the worst case, the exact variance of the cross-correlation was estimated by using all possible code sequences and their all-possible cyclic shifted versions. The resulted variances are shown in Table 3. The SNR for each code could be obtained from Eq. (11).

The calculated probability of errors for the optical CDMA system with ARC is illustrated in Fig. 5. The results show that the ART could generate codes having the same BER as the prime-hop code for $F = 25$ or better BER for $F = 45$ under the same conditions than that of the eqc-prime code proposed for massive LANs (Fig. 5) where the prime-hop code has ideal properties that are the maximum autocorrelation sidelobes of 0 ($\lambda_a = 0$) and cross-correlation constraint of 1 ($\lambda_c = 1$) for $F = 25$ and the eqc-prime code is one of the TWH 2-D codes with the largest cardinality reported in the literature.

A system designer can easily assign more address codes than the initial available codes in an existing network by generating ARC set with increased cardinality at the expense of the minimum performance degradation. Hence, the network can accept additional subscribers via amendment of software in the encoding/decoding process without any physical or structural changes. On the other hand, other schemes [2–5,12] require the drastic modification of the system such as encoder/decoder with increased chip rate and the number of wavelengths or pulses used in the coding of the data. Fig. 6 demonstrates that the performance of the system is slightly affected when the ARC code sets with increased cardinalities from 20 to 46 and from 40 to 80 under the same conditions are implemented.

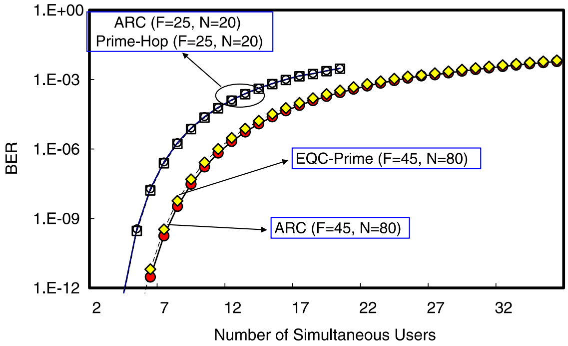

Fig. 5. BER comparison of optical CDMA systems with ARC, prime-hop and eqc-prime codes for $S = 5$, $H = 5$.

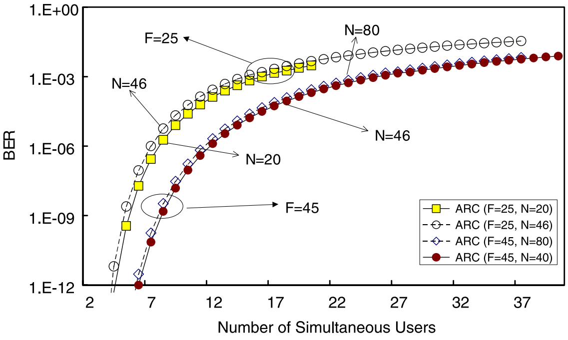

Fig. 6. Influence of increase of cardinality on BER for $S = 5$, $H = 5$.

In order to evaluate the performance of the ARC in more universal framework than BER, a normalized throughput metric was adopted [15]. At high offered loads over 30 packets per packet-slot, the calculated peak normalized throughput of

Table 3
Estimated variances of cross-correlation values for various TWH code families in worst case for $S = H = 5$

Code family	$F = 25$ $N = 5$	$F = 25$ $N = 20$	$F = 25$ $N = 46$	$F = 45$ $N = 46$	$F = 45$ $N = 80$
ARC	0.16	0.16168	0.17948	0.10096	0.10432
PH	0.16	0.16	Imp	Imp	Imp
EP	Imp	Imp	Imp	0.10777	0.10777

Imp: impossible, PH: prime-hop, EP: eqc-prime.

ARCs exceeded 0.06 while for the MWOOC, OOC and prime-hop code, 0.044, 0.035 and 0.012, respectively, have been reported in [15]. The results show that the proposed ARC has the best performance among the four code families.

5. Conclusion

The chip rate ($r_c = r_b \times F$) is only determined by the data bit rate r_b of each user and the length of each signature sequence F. The available maximum chip rate, however, depends on many factors, including the minimum pulse width determined by the state-of-the-art technology, the aimed number of nodes, the encoding scheme, the available number of wavelengths and tolerable mismatches between the encoder and desired decoder, i.e., both the encoder and decoder have delay-lines with different length and grating devices with different center wavelengths. Once the system parameters are determined, the ARC set, with the optimal performance under the given conditions, can be generated.

In conclusion, we have introduced a novel code, ARC, to implement a flexible optical CDMA system. The most important issue in an asynchronous optical CDMA system is the MAI caused by the non-ideal orthogonal property of optical codes since the MAI is the main cause of the system performance degradation. The generated ARC codes have shown smaller MAIs for any weight S, the number of wavelengths H, code length F and cardinality N than other codes.

In addition, the analytical results have demonstrated that when the cardinality of the code set with $F = 45$, $S = 5$ and $H = 5$ is increased from 46 to 80, the bit error probabilities of the system remains in the same order where the cardinality of 80 is the same value as the eqc-prime code with the largest cardinality reported in the literature [5] for the same F, S and H, and the performance is better than that of the eqc-prime code. The proposed ARC provides an elastic method to implement the optical CDMA system since the proposed code has the minimum MAI under the arbitrary restrictions.

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