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Design and Analysis of Optical CDMA System Based on Application of Code Shifting Technique to 2-D Optical Orthogonal Codes

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ABSTRACT*:* The use of Two-dimensional (2-D) codes for optical CDMA(OCDMA) are important due to the large code set size(cardinality) of such codes and their good spectral efficiency, when compared to one-dimensional (1-D) codes. Two-dimensional matrix codes can be generated by means of golomb rulers. For OCDMA applications these matrices can be interpreted as space/time (S/T) or wavelength/time (W/T) matrix codes. In this paper, a code-shifting technique, which can be applied in asynchronous optical code-division multiple-access systems without complex modifications, is proposed. By this technique the time-slots (or chips) are divided, in which the optical pulses of codewords are present, into g equal-width sub-chips. Here every pulse is randomly and independently shifted in such a way to start at one of the g sub-chips of its own chip, where g is a positive integer greater than 1. The paper describes the design and construction of the PSO matrices; application of a code shifting technique; analyzes their performance; describes their use as codes for the asynchronous communication of multiple users; and analyzes the bit error rate performance.

KEYWORDS*:* Optical code-division multiple access (OCDMA), encoding, matrix codes, multi access communication, optical fiber communication.

I. Introduction

Optical code-division multiple access (OCDMA) has inherent ability to support asynchronous bursty communications. As such, it was initially pursued for local area [1] and then for access network applications [2]–[5]. Generally, OCDMA can be divided into direct-sequence pseudoorthogonal (PSO) pulse sequences [6], which are referred to as optical orthogonal codes (OOCs) [7], [8]; direct sequence bipolar codes; frequency or phase encoding codes, sequence bipolar codes; frequency encoding codes, so on; and two-dimensional (2-D) and higher dimensional codes [9-13].

The choice of suitable asynchronous unipolar optical codes is an important factor in designing the incoherent O-CDMA systems because this determines the amount of MAI (Multiple Access Interference) caused by simultaneous user which in turn, affects the error probability, of the incoherent O-CDMA systems. The use of one-dimensional (1-D) and two-dimensional (2-D) optical codes with very low cross-correlation constraints (of at most one or two) usually minimizes the MAI. Besides the periodic cross-correlation functions, code parameters, such as code length (i.e., number of time-slots or chips), code weight (i.e., number of pulses in each codeword), and the number of available wavelengths (for 2-D codes) can also be adjusted (or increased) to minimize the "hit probability" in the cross-correlation process and, in turn, improve the error probability [14]–[22]. Once the systems have been designed or implemented it is difficult to change the optical codes or code parameters. In this paper, a specific set of W/T codes are designed and implemented in OCDMA system. It then describes a code-shifting technique and show how it improves performance without complex system modifications.

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II. THEORY, ANALYSIS, AND SIMULATION

A. Construction of the Matrix Codes

A family of Two-Dimensional Wavelength-Time Codes is designed to increase the performance of optical system. In the proposed architecture for Optical CDMA the transmitter uses 2-D PSO codes for the coding of transmitted signal. Pseudo-orthogonal matrix codes are developed based on the "folding" of available spanning rulers or optimum Golomb rulers to produce the matrix codes for Optical CDMA networks.

An optimum Golomb ruler is defined to be a binary pulse sequences, the entries in the ruler are such that pulses occurring once, after any integer value in the matrix, never repeat the same for further generation of matrix elements [17],[23]. Optimum Golomb ruler is described as the shortest length ruler with points such that all distances between any of the two points are not repeated. While these rulers have other mathematical applications, the interest to us is that they can be used as starting points for generating two-dimensional (2-D) codes.

$$g1(4,4)=\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}\hline 1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&1\\\hline\end{array}$$

$$g2(4,4)=\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}\hline 1&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&1&0\\\hline\end{array}$$

$$g3(4,4)=\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}\hline 1&0&0&0&0&0&0&0&0&1&0&0&0&0&1&0&0&0&0&0&0&1&0&0&0\\\hline\end{array}$$

$$g4(4,4)=\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}\hline 1&0&0&0&1&0&0&0&0&0&0&0&0&0&0&1&0&1&0&0&0&0&0&0&0\\\hline\end{array}$$

Fig.1. Golomb rulers of weight four

The top of fig.1 gives the one of the Golomb ruler $g1(4,4)$ having cardinality 4, weight 4 and length 26. Filler zeroes are appended to these rulers sufficient to form the code dimension CD=32. Then it can be folded to get 8×4 matrix code. Row wise shifting is applied to the generated matrix which gives additional matrices preserving their orthogonality. By using same procedure, different codes can be generated for OCDMA system. The fundamental ruler $g1(4,4)$ produces the matrix $M1$, $g2(4,4)$ produces $M9$, and $g3(4,4)$ creates $M17$, and $g4(4,4)$ creates $M25$. By cyclic row shifting $M1$ produces $M2 \ldots M8$; $M9$ produces $M10 \ldots M16$; $M17$ produces $M18 \ldots M24$, and $M25$ produces $M26 \ldots M32$.

Cyclic row shifting can be represented by the matrix operator P given by,

$$P=\begin{bmatrix} 0&0&0&0&0&0&0&1\\ 1&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0\\ 0&0&1&0&0&0&0&0\\ 0&0&0&1&0&0&0&0\\ 0&0&0&0&1&0&0&0\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&1&0 \end{bmatrix}$$

and then the matrices Mi are generated by

$$Mi = (P^{\wedge (i)})^{*} M1 \text{ (or M9, M17,M25)} \tag{1}$$

Where i= 0,1….7

This way the codes with desired the correlation properties are obtained. But it is not valid for some instances where there is a shifting of "1" in P from the last row to the first row of the resultant matrix code structure. Then the resulting matrix is needed to be "fixed". It is then achieved with the help of an operator which provides the desired shift to the cells except mentioned exceptional case.

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$$M1j = M1j+1 \quad (2)$$

(Where $M1j$ is an element present in the first row of the matrix obtained after operator P shifts it from the former row of the previous matrix). For example M10=P*M9, M19=P*M18, M26=P*M25 etc. needed to be fixed in this way [13],[17].

Table.1. 32 PSO matrix codes interpreted as W/T matrix code

Wavelength	Time slots (s)			
(W)	1	2	3	4
1	1,9,17,25	1,14,29	19,24,26	1,7,10,11,20,32
2	2,10,18,26	2,15,17,30	20,25,27	2,8,11,12,21
3	3,11,19,27	3,16,18,31	1,21,26,28	3,12,13,22
4	4,9,12,20,28	4,19,32	2,22,27,29	4,13,14,23
5	5,10,13,21,25,29	5,20	3,23,28,30	5,14,15,24
6	6,11,14,22,26,30	6,21	4,17,24,29,31	6,15,16
7	7,12,15,23,27,31	7,17,22	5,9,18,30,32	7,16
8	8,13,16,4,28,32	8,18,23,25	6,9,10,19,31	8

The generated PSO matrixes are converted to wavelength/time (W/T) codes by associating the rows of the PSO matrixes with wavelength and columns with time slots, as shown in Table.1. The matrixes M1…M32 are numbered 1…32 in the table, with the corresponding assignment of wavelength and time slots.

B. Code shifting technique

In the code-shifting technique, each timeslots (or chips) of the optical pulses in every codeword can be subdivided into g sub-slots (or sub-chips) of equal width. Here it is defined as the *timeslot granularity*. Every pulse is randomly and independently shifted in such a way to start at one of the g sub-chips of the chip where the pulse is originally located. Due to this random shift, the cross-correlation property of the optical codes in use is changed, and this, in turn, affects the code performance, as both now become a function of g. Due to the g-shift the pseudo-orthogonality of the optical codes was broken. On the other hand, finer time-slot granularity (i.e., larger g) increases the number of possible "pulse locations" in codewords, and thus reduces "hit" probabilities during the cross-correlation process. By increasing the code parameters, such as length, weight, and number of wavelengths (in 2-D optical codes) system (or code) performance can only be improved. Due to hardware or bandwidth limitations in the number of time-slots (i.e., chips) or wavelengths these code parameters may not be easily changeable. But the code shifting technique here improves the performance without changing the code parameters [24], [25].

The design of an O-CDMA system with the proposed code-shifting technique includes the following steps:

1) Select a family of (W × T, w, λc) 2-D optical codes, which consists of W × T binary matrices (i.e., codewords) with W wavelengths, T time-slots (i.e., code length), w pulses (i.e., weight), and the maximum cross-correlation constraint of λc [15], [16]. In general, the w pulses of every 2-D codeword, say codeword i, in the code set can be represented as w ordered pairs such that $C_i = [(\lambda_0, t_{\lambda 0}), (\lambda_1, t_{\lambda 1}), \ldots, (\lambda_{w-1}, t_{\lambda w-1})]$. Here each ordered pair denotes that the optical pulse of wavelength λ_j is located in time-slot position $t_{\lambda j} \in \{0, 1, \ldots, T-1\}$ for $j \in \{0, 1, \ldots, w-1\}$.

2) Select the amount of *time-slot granularity* g to use. A positive integer should be selected as the value of g (g > 1). In every codeword the time-slots (or chips) in which the pulses are present is subdivided into g sub-slots (or sub-chips) of equal width. The fig.2a shows the original code words (C_1 & C_2) with their pulse positions (black shade). Each of these pulses can be independently and randomly shifted to start at one of the g sub-chips of its own chip location.

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3) To the original chip position of the associated optical pulse a random sub-chip-shift value is added to indicate the new chip-plus-sub-chip position after shifting. Such a random shift can be equivalently represented in terms of time delay. Assuming that the width of a chip is equal to 1, then the width of each sub-chip is 1/g. A new time-delay factor $\tau_{g,j,sj} \in \{0, 1/g, 2/g, . . . , (g - 1)/g\}$ is defined as the corresponding (sub-chip) time delay of the jth optical pulse (for 1-D codes) or the optical pulse of the jth wavelength (for 2-D codes), where $j \in [0,w - 1]$. The term s_j is a random integer taken from the set of $\{0, 1, 2, . . ., g - 1\}$, corresponding to the sub-chip where the jth optical pulse begins. Then, the ordered pairs of the "shifted" codeword of Ci become $[(\lambda_0, t_{\lambda 0} + \tau_{g,0,s0}), (\lambda_1, t_{\lambda 1} + \lambda_{g1,s1}), . . . , (\lambda_{w-1}, t_{\lambda w-1} + \tau_{g,w-1,sw-1})]$, where $\tau_{g,0,s0}$, $\tau_{g,1,s1}$, . . ., and $\tau_{g,w-1,sw-1}$ are all randomly picked from the set of $\{0, 1/g, 2/g, . . . , (g -1)/g\}$ and these time delays need not be identical.

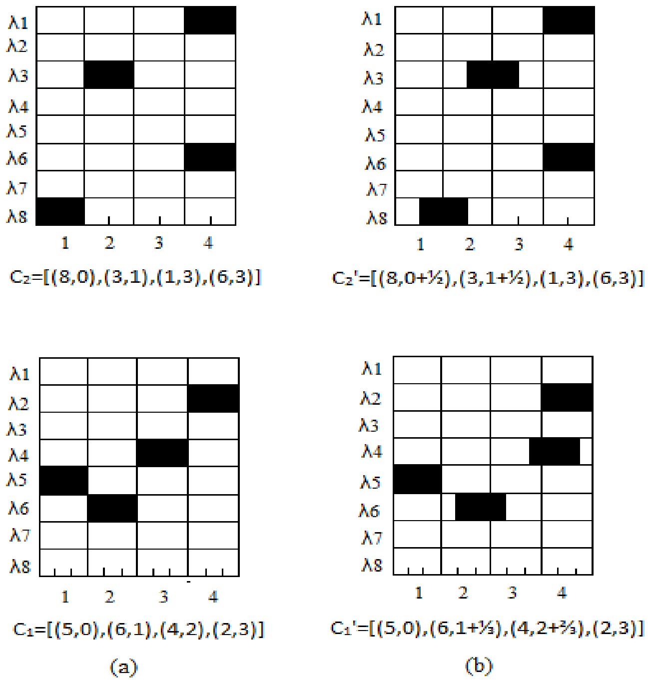

Fig.2. Examples of code shift (g = 2 & g=3) being applied to the pulses of 2-D codeword: (a) the original codeword without any pulse shift; b) a shifted copy of the codeword

Fig.2b shows the shifted copy of the codewords (C_1' & C_2') after the application of code shifting technique. Codeword C_1 is applied with g=3 and C_2 with g=2. Then the positions of pulses are randomly shifted by providing corresponding time delay.

C. System simulation

In the simulation model optical CDMA transmission link (Fig.3), 2.5 Gbps data signal was generated with NRZ modulation. The 2.5 Gbps NRZ data signal was then modulated by means of MZ modulator and then transmitted over Single mode (SM) fiber. A CW laser array was used to create a multi-frequency light source of 10 mW operating at 1543.74-1549.34nm with 0.8nm spacing.

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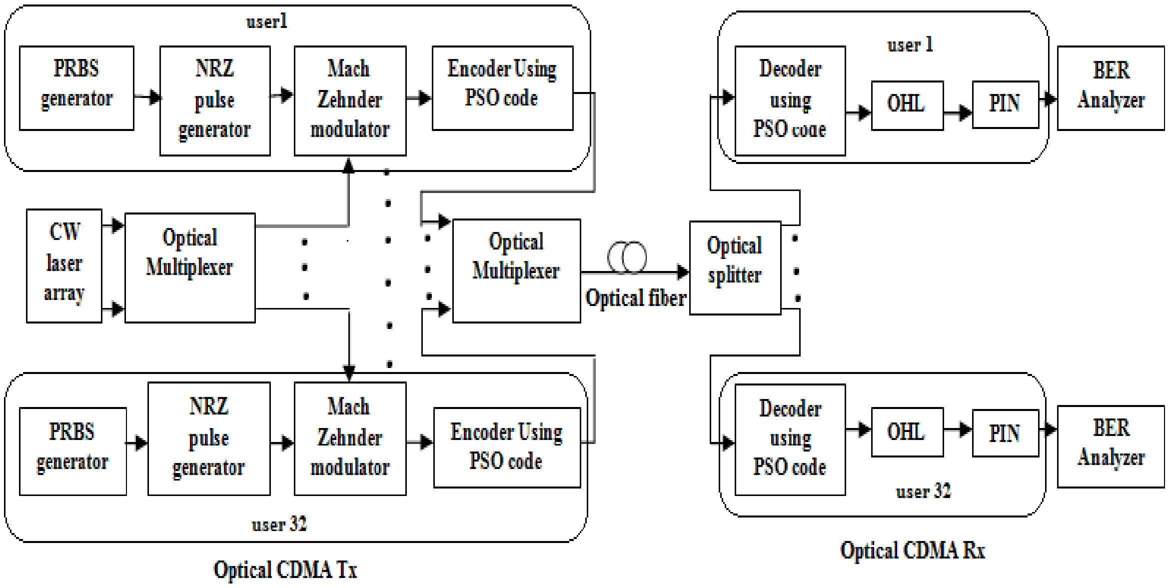

Fig.3. Schematic of simulation setup for OCDMA transmission link

After modulation an encoder was used for encoding signal according to the PSO code. Modulated signal are distributed to respective encoders, which have been assigned a unique W/T code respective to each encoders. The generated wavelength/time (W/T) matrix codes uses 8 wavelengths and 4 time slots. Fig.4a shows the design of an encoder having four optical filters and four shift signals are used to produce encoded bit steam. Uniform fiber bragg gratings are used to filter out spectral wavelengths and optical delay units to provide delay in terms of integer multiple of chip time (CT).

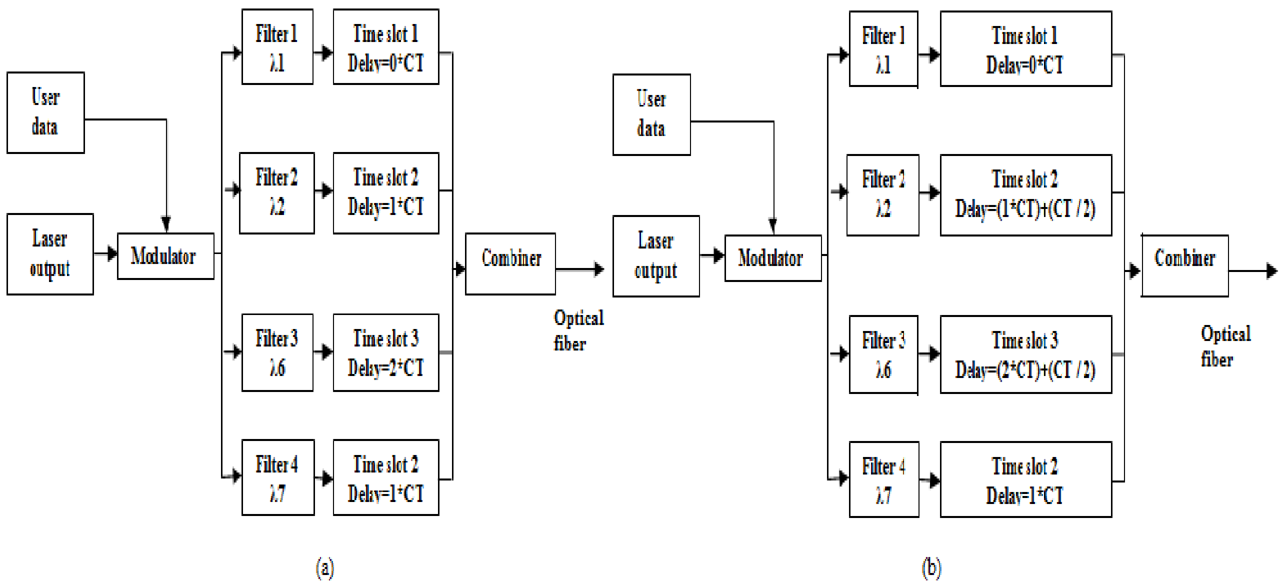

Fig.4. Encoder design for OCDMA system: (a) without code shifting (g=1); (b) after the application of code shifting (g=2)

Encoded data is send through single mode fiber followed by optical amplifier. At the receiver information is retrieved by a decoder using the same OOC with the help of FBGs and inverse delay lines. Optical hard limiters (OHL) are introduced to reduce the effect of Multi Access Interference (MAI). Then the optical signal was converted back into

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electrical form through a PIN photo diode and hence 2.5Gbps optical CDMA data is recovered successfully. The bit error rate of the system corresponding to different number of users has been verified.

Secondly the code shifting technique was applied (fig.4b) to each codeword by dividing the chips into g sub-slots and time shifting was applied randomly. It was not necessary to apply the shift to all time slots. Once shifting was done shifted codes have been applied to the designed OCDMA system. The system was redesigned for g=2 and g=3.

III. RESULTS AND DISCUSSION

The proposed system has been designed for optimum results in favor of BER for multiple users operating at 2.5Gbps data rate. PSO matrices from sets of optimum Golomb ruler have both a higher cardinality and higher Spectral Density than the rulers from which they are derived and they can be used as unipolar codes for designing OCDMA local or access networks where the transceivers use intensity modulation and direct detection (IM/DD). These matrices can be interpreted (designed and implemented) as matrix codes. Simulations and measurements with the W/T code indicate that the visibility of the signal over the MAI is good enough to produce BERs of $10^{\wedge -13}$ for up to 16 concurrent users.

Table.2. BER observations for number of active user

No. of user	BER		
	g=1	g=2	g=3
2	1.69419e-227	1.24915e-251	4.19448e-268
4	1.34945e-70	7.36992e-082	5.1224e-096
8	3.52326e-34	9.92392e-045	7.37987e-069
12	3.51841e-23	8.97442e-035	6.98823e-057
16	2.49461e-13	6.72725e-026	1.02766e-044
20	2.55977e-10	1.4261e-020	3.0767e-032
24	7.64251e-7	1.87178e-015	6.09361e-022
28	1.0436e-4	1.57686e-012	2.75043e-018
32	3.9421e-2	2.19453e-009	3.16106e-014

When the code shifting technique is applied in the generated PSO matrix codes the pulses in each codeword are being shifted randomly and independently to any of the g sub-chips in the pulses' original chips.

From the graphical representation (fig.5) it can be observed that as the as g increases the g-granulated hit probabilities get reduced because finer time-slot granularity increases the number of possible locations for the pulses in each codeword. The result shows that the code shifting technique provides improvement in BER performance when compared with the simulation results of OCDMA system with no code shift. Thus the number of concurrent users gets increased to 32.

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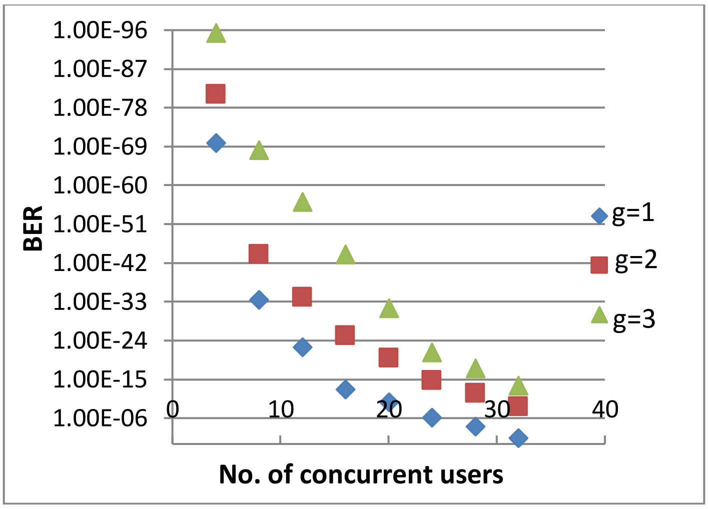

Fig.5. BER vs number of concurrent users with (g=2 & g=3) and without (g=1) code shifting.

IV. CONCLUSION

With the advancement in technology, there is continuous need of OCDMA systems with more number of users at higher bit rates. Obtained results for 2D-W/T coded OCDMA system specify that for large number of users at high data rate, i.e, 2.5 Gbps, received optical power decreases and simultaneously there is increase in BER value at the receiver. The code shifting technique proposed here improves the BER performance of the OCDMA system and hence the number of active users without changing the code parameters. It is also observed that as the time-slot granularity gets finer (g increases) the system performance shows improvement.

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