Novel Combinatorial Constructions of Optical Orthogonal Codes for Incoherent Optical CDMA Systems

Ivan B. Djordjevic and Bane Vasic, *Senior Member, IEEE*

***Abstract*—Three novel classes of optical orthogonal codes (OOCs) based on combinatorial designs are proposed. They are applicable to both synchronous and asynchronous incoherent optical code-division multiple access (OCDMA) and compatible with spectral-amplitude-coding (SAC), fast frequency hopping, and time-spreading schemes. Simplicity of construction, larger codeword families, and larger flexibility in cross-correlation control make the proposed OOC families interesting candidates for future OCDMA applications. A novel balanced SAC receiver for multiuser interference cancellation that can handle unequal in-phase cross correlation of OOC is also proposed. The upper bound on the bit-error rate as a function of the number of users in SAC schemes is given for all proposed OOC classes.**

***Index Terms*—Affine geometries, balanced incomplete block designs (BIBDs), fast frequency hopping, integer lattice design, mutually orthogonal Latin squares/rectangles (MOLSs)/(MOLRs), optical orthogonal codes, spectral-amplitude-coding (SAC), time-spreading encoding.**

I. Introduction

THE OPTICAL code-division multiple-access (OCDMA) systems have experienced increasing research attention in the last decade [1]–[4], [6]–[10] because they offer several attractive features, such as asynchronous access, privacy and security in transmission, ability to support variable bit rate and bursty traffic, and scalability of the network.

Discrimination of an unwanted signal is achieved by assigning minimally interfering spreading sequences to each user, selected from a family of so-called optical orthogonal codes (OOCs). Recently, a number of OOC families have been proposed [1]–[4], [6]–[10] for various OCDMA technologies. For example, OOC constructed by Wei, Shalaby, and Ghafouri-Shiraz are designed for spectral-amplitude-coding (SAC) [2], [4], [10]. Salehi [1] and Chung *et al.* [3] constructed another family of OOC suitable for time-spreading systems, while Fathallah *et al.* [8] designed OOC for fast frequency-hopping schemes. The motivation for this paper is the realization that, from a coding theory point of view, construction of OOC is independent of the CDMA technology and that the maximum values of off-peak autocorrelation cross correlation can be controlled by varying the "combinatorial" parameters of the code.

We present three novel OOC classes based on mutually orthogonal Latin squares (MOLSs) or mutually orthogonal Latin rectangles (MOLRs), integer lattice design and affine geometries (AGs), and all subdesigns of balanced incomplete block designs (BIBDs). The major advantages of proposed OOC families are: 1) large flexibility in choosing the number of users (code size); 2) simplicity of construction; 3) larger number of parameters and, consequently, more OOC families; and 4) suitability to all important transmission technologies. The latest feature means that the proposed OOC families can be applied to both synchronous and asynchronous incoherent OCDMA and for all of the following classes of systems:

1) spectral-amplitude-coding;
2) fast frequency-hopping;
3) time-spreading schemes.

Spreading sequences of MOLS/MOLR, integer lattice, and AG OOC families can be partitioned into "parallel" classes in such a way that the sequences from different parallel classes have zero cross correlation, which makes this class attractive for OCDMA applications. For example, in fiber Bragg grating (FBG) implementations, the adjacent frequency bands are not ideally decoupled, and two sequences that involve adjacent bands should have zero cross correlation. A novel balanced multiuser interference (MUI) cancellation scheme supporting the proposed unipolar code families is proposed. The number of mutually orthogonal spreading sequence classes is expressed in a closed form as a function of the combinatorial design parameters. It is used to obtain an upper bound on the bit-error rate (BER) as a function of the number of users.

II. Spectral Amplitude Coding Schemes

In spectral-amplitude-coding OCDMA unipolar OOC having fixed in-phase cross correlation were the only codes considered so far, as they require a simple balanced detection scheme proposed in [4] to eliminate MUI and suppress the phase-induced intensity noise.

Let $x = (\mathrm{x}_1, x_2, \ldots, x_\nu)$ and $y = (y_1, y_2, \ldots, y_\nu)$ be two different code sequences, and let their mutual in-phase cross correlation be defined as

$$R_{x,y} = \sum_{n=1}^{v} x_n y_n. \quad (1)$$

Manuscript received July 26, 2002; revised March 13, 2003.

I. B. Djordjevic is with the Department of Electrical and Electronic Engineering, Optical Communications Research Group, University of Bristol, Bristol BS8 1TR, U.K. (e-mail: Ivan.Djordjevic@bristol.ac.uk).

B. Vasic is with the Department of Electrical and Computer Engineering, University Arizona, Tucson, AZ 85721 USA (e-mail: vasic@ece.arizona.edu).

Digital Object Identifier 10.1109/JLT.2003.814932

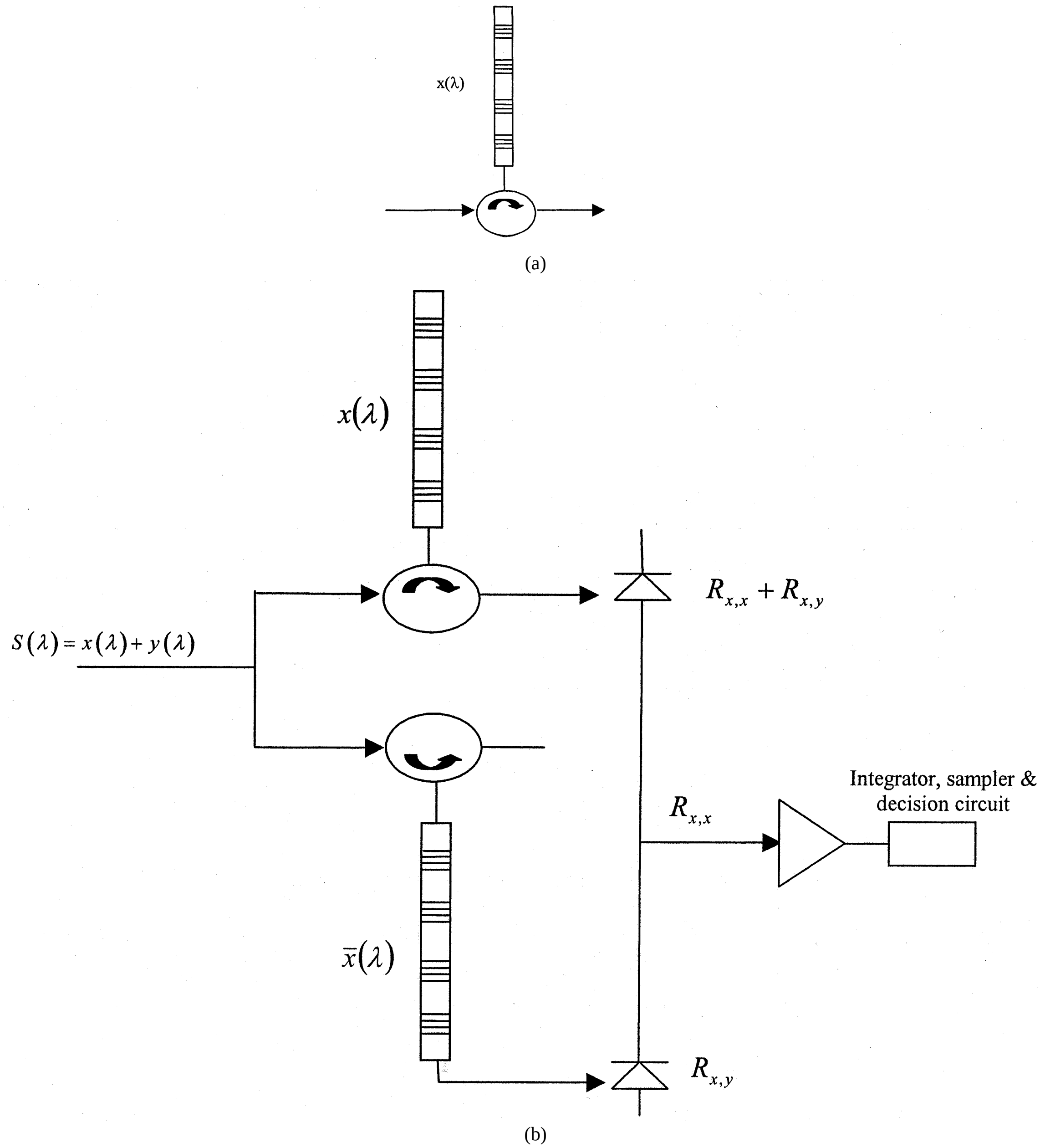

Fig. 1. Proposed SAC (a) encoder and (b) balanced MUI cancellation decoder scheme.

If sequences have the two properties $R_{x,\bar{x}} = 0$ and $R_{x,y} = R_{\bar{x},y}$, then MUI can be cancelled by the balanced detection scheme [4]. We propose a novel FBG-based balanced detection scheme that allows the MUI cancellation in the case when unipolar sequences having in-phase cross correlation 0 or 1 are employed. Such a scheme allows using sequences with less stringent in-phase correlation constraints, and, as a consequence, much larger code families may be constructed. The simplest OCDMA network consists of N transmitter/receiver pairs connected in a star configuration [1]. To send the information from the ith to jth user, the address code for the receiver j is impressed upon data by the encoder at the ith node. The transmitter and receiver structures based on FBGs are shown in Fig. 1. When bit "1" is sent, an optical pulse from a broad-band source is launched into the encoder, and no optical pulse is launched for data bit "0". The optical pulse passes through the linear FBG array in encoder and corresponding spectral components, according to the spectral distribution $x(\lambda)$ (position of ones within a codeword), are reflected. For the reconfiguration of the destination address code, all gratings in the encoder are tunable. At the receiver, each grating is fixed according to the receiver's address. For proper decoding, the peak wavelengths are arranged in opposite order so that round-trip delays of different spectral components are compensated (all reflected components have the same delay and can be merged into a pulse again). The lower balanced detection part is used to estimate the MUI, and the upper for desired code detection. The MUI is completely removed for every class of unipolar codes proposed here.

The balanced receiver proposed in [4] requires that the sequences have fixed in-phase cross correlation. Since such sequences satisfy $R_{x,y} = R_{\bar{x},y}$, the MUI can be completely removed. In our balanced decoding scheme [Fig. 1(b)], the signal at the upper photodiode is proportional to $R_{x,x} + R_{x,y}$ (with x being the desired sequence, and y the interefering sequence), and the signal at the lower photodiode is proportional to $R_{x,y}$. From Fig. 1(b), it can be seen that the MUI is completely removed with balanced detection. Since our decoding scheme does not require sequences having fixed in-phase cross correlation, for a given codeword length, OOC family has much more spreading sequences, as shown in Sections IV–VI.

III. OOC Based on Combinatorial Designs

Following Salehi's notation [1], we define an OOC (v, k, $\lambda_{\rm a}$, $\lambda_{\rm c}$) as a family of (0, 1) sequences of length v and weight k with the maximum value of off-peak autocorrelation $\lambda_{\rm a}$ and the maximum value of cross correlation $\lambda_{\rm c}$. The construction and performance analysis of optical orthogonal codes for OCDMA have been investigated extensively [1]–[4], [6]–[10]. The research has focused on the $\lambda_a = \lambda_c = \lambda$ case [1]–[4], [7]–[10] [such codes are often abbreviated as OOC (v, k, λ)].

An alternative and convenient way of representing optical orthogonal codes (also called here *codewords*), especially when the weight k is much smaller than length ν, is using combinatorial designs. A support set of the OOC is described as a set of positions of nonzero elements in spreading sequences. The OOC is then a collection of size k integer sets. Therefore, an OOC can be represented as a combinatorial t design [5]. A similar approach was initially suggested by Chung *et al.* [3]. A t design, denoted as $t - (v, k, \lambda)$, is a collection of k subsets of a v set V such that every t subset of V is contained in *exactly* λ blocks. Our construction uses designs such that every t subset of V is contained in *no more* than λ blocks and can be denoted by $t - (v, k, \{0, \ldots, \lambda\})$. In combinatorial literature, such designs are referred to as λ configurations. BIBD is a $2 - (v, k, \lambda)$ design. Latin squares/rectangles, integer lattice construction, and affine geometries, considered here, are in fact special classes of BIBDs and 1-configurations.

IV. OOC Based on MOLRs

A $m \times k$ integer array $[L_k(x, y)]_{1 \le x \le k, 1 \le y \le m}$ with elements $L_k(x, y)$ in $\{0, 1, \ldots, m\}$ is referred to as a *Latin rectangle* if each of the elements occurs once in each row and once in each column. For two rectangles $L_k^1 = [L_k^1(x, y)]_{1 \le x \le k, 1 \le y \le m}$ and $L_k^2 = [L_k^2(x, y)]_{1 \le x \le k, 1 \le y \le m}$, the *join* ($L_k^1$, L_k^2) of L_k^1 and L_k^2 is the $m \times k$ array whose (x, y)th entry is the pair ($L_k^1(x, y)$, $L_k^2(x, y)$). Two Latin rectangles L_k^1 and L_k^2 are *orthogonal* if all entries in the join are distinct. Latin rectangles $L_k^1, L_k^2, \ldots, L_k^n$ are *mutually orthogonal* if they are orthogonal in pairs.

Let us explain the MOLR construction of equal sizes (i.e., MOLS). This construction is based on elementary combinatorics (see, e.g., [5]). For the sake of illustration, let the dimensions of squares be $k = m = p^l$, p is a prime, and $l \ge 1$, and let $\alpha_0 = 0, \alpha_1, \alpha_2, \ldots, \alpha_{k-1}$ be the elements of $GF(k)$. Consider the nonzero element α and define a $k \times k$ array L_k^α with elements $L_k^\alpha(x, y) = \alpha \cdot \alpha_x + \alpha_y$, $0 \le x, y \le k - 1$. It can be shown that the arrays L_k^α, $0 \le x, y \le k - 1$ are MOLSs of order k [5]. Consider now a $k \times k$ integer lattice $L = Z_k \times Z_k$ with elements labeled by the points from the set V. In other words, let $l : L \to V$ be a one-to-one mapping of the square L to the integer set V of a design. An example of such mapping is a simple linear mapping $l(x, y) = m \cdot x + y + 1$. The numbers $l(x, y)$ are referred to as cell labels. Each L_k^α defines a set of k parallel lines $B_k^\alpha = \{l(x, y) : L_\alpha(x, y) = s\}$, $0 \le s \le k - 1$. The slopes $s = 0$ and $s = \infty$ can be also included to create a full resolvable BIBD with $v = k^2$, $b = k(k+1)$ and $r = k+1$, which corresponds to an OOC family of cardinality b, codeword length n, and codeword weight k. The corresponding design for $GF(4)$ with the resolvability classes shown in different columns is given in Table I. The columns correspond to lines of different slopes. For example, the lines of slope $s = \alpha_1$ contain the points with labels {1, 6, 11, 16}, {2, 5, 12, 15}, {3, 8, 9, 14}, and {4, 7, 10, 13}, respectively. The corresponding codewords are (1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1), (0 1 0 0 1 0 0 0 0 0 0 1 0 0 1 0), (0 0 1 0 0 0 0 1 1 0 0 0 0 1 0 0), and (0 0 0 1 0 0 1 0 0 1 0 0 1 0 0 0), respectively.

For asynchronous time-spreading CDMA applications, the codewords that are cyclic shifts of the previous ones must be omitted, which reduces the number of codewords.

Let us now explain how the above OOC can be used in different OCDMA systems. The application in time-spreading systems (such as the system using optical tapped delay line) is straightforward, the spectral-amplitude-coding systems are considered in a separate section (Section II), while the fast-frequency-hopping scheme is described in the remainder of the section. In the optical fast-frequency-hopping CDMA system, the labels of points in Table I should be viewed as different frequencies from a finite set of frequencies, a line is assigned to a particular user, and four points of each line define the (ordered) set of frequencies assigned to a particular user in the consecutive chip time slots. There are no frequency hits in any chip time interval.

In our example, there are four users, 16 frequencies, and four time slots. In the first time cycle, the frequencies should be assigned according to the column with slope $s = \infty$ (from Table I), in the second from the slope $s = 0$, and so on, until all slopes are exploited. The same assignment rule is repeated in every bit interval. The antijamming can be realized by randomly changing the slope-user assignment from a bit interval to a bit interval.

Another approach to the fast-frequency-hopping scheme is to consider the labels in Table I as different frequencies, chosen from a set of allowed frequencies. Each codeword is assigned to a particular user, and frequencies corresponding to a given codeword are used in consecutive chip time slots. Therefore, the design supports b users, there are k time slots (chips) in a bit interval, and there are v frequencies in a set of frequencies. No more than one frequency hit between any two users appears during every chip interval.

The Latin rectangle with different horizontal and vertical dimensions can be defined in a similar way (m should be a prime power, and m and k should be mutually prime). Instead, the MOLR counterpart-integer lattice design will be presented in the next section.

Notice that the codewords corresponding to parallel lines are orthogonal to each other. Any two points are connected by only one line. Two lines are either parallel (they do not have points

TABLE I
LINES OF MOLS CONSTRUCTED FROM $GF(4)$

s=∞	s=0	α_1	α_2	α_3
1 2 3 4	1 5 9 13	1 6 11 16	1 8 10 15	1 7 12 14
5 6 7 8	2 6 10 14	2 5 12 15	4 5 11 14	3 5 10 16
9 10 11 12	3 7 11 15	3 8 9 14	2 7 9 16	4 6 9 15
13 14 15 16	4 8 12 16	4 7 10 13	3 6 12 13	2 8 11 13

in common) or intersect in only one point. Therefore, two codewords have at most one "1" in common.

V. OOC BASED ON INTEGER LATTICE DESIGN

The designs are lines connecting points of a rectangular integer lattice. The subsets of points (but not all subsets) are referred to as lines, and the design is defined as a set of lines of different slopes.

A *line with slope* s, $0 \leq s \leq m-1$, *starting at* the point (x, a), contains the points

$$\{(x, a + sx \bmod m) : 0 \leq x \leq k-1\} \quad (2)$$

where $0 \leq s \leq m-1$. The total number of lines is equal to m^2. Therefore, the maximum number of users is m^2, the codeword length is $m \cdot k$, and the codeword weight k. It can be readily verified that arbitrary large families are possible as long as m and k are co-prime.

To illustrate the code construction for synchronous CDMA applications, we provide an example of a small lattice of dimensions $m = 7$ by $k = 3$, shown in Fig. 2. The lines of slopes $0 \leq s < 7$ form a 2-(21,3,{0,1}) design, which is a support set of an OOC family with codeword weight $k = 3$. In other words, each line of a design specifies positions of nonzero elements in a codeword, and the resulting design is given in Table II. The columns correspond to lines of different slopes in Fig. 2. For example, the lines of slopes 0, 1, 2, 3, 4, 5 and 6 starting at (0,1) in Fig. 1 contains the points with labels {2, 9, 16}, {2, 10, 18}, {2, 11, 20}, {2, 12, 15}, {2, 13, 17}, {2, 14, 19}, and {2, 8, 21}, respectively. The corresponding codewords are (0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0), (0 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 1 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 1 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 0), (0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0), (0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1 0 0), and (0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1), respectively.

The main difference between OOC for synchronous and asynchronous time-spreading CDMA applications is that, in asynchronous OCDMA, no cyclic shifts are permitted. In other words, if c is a codeword, then no cyclic shift of c is a codeword. Therefore, to get an OOC for an asynchronous OCDMA application, we can use the same construction and then eliminate cyclic shifts.

In the optical fast-frequency-hopping OCDMA system, the labels of points in Fig. 2 should be viewed as different frequencies from a finite set of frequencies, and the x axis should be considered as the chip time-slots axis. The users are associated with the slopes in such a way that a line of a given slope defines a frequency-time pair assignment for a particular user, i.e., defines the (ordered) set of frequencies assigned to a particular user in the consecutive chip time slots.

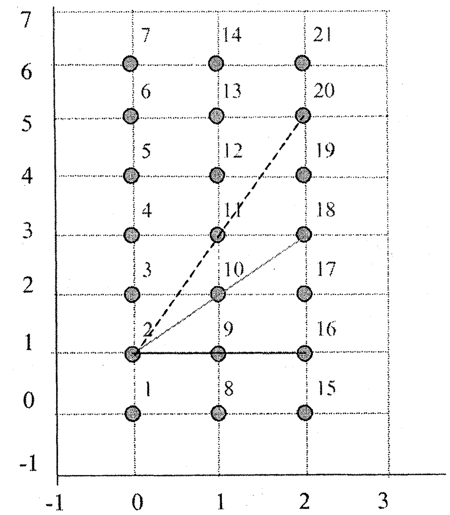

Fig. 2. Example of the integer rectangular lattice for $m = 7$ and $k = 3$.

In our example, there are seven users, 21 frequencies, and three time slots. In the first time cycle, the frequencies should be assigned according to the column with slope $s = 0$ (from Table I), in the second from the slope $s = 1$, and so on until all slopes are exploited. The same assignment rule is repeated in every bit interval. The antijamming can be realized by randomly changing the slope-user assignment from a bit interval to a bit interval. More generally, integer lattice support m users (vertical dimension of the lattice), mk frequency (each particular label from Table II denotes different frequency) are employed and k chips during a bit duration with no frequency hits during any chip interval.

With at most one hit per chip, the design cardinality increases to m^2, and there are again mk frequencies in a set and k chips within a bit interval. For this frequency-hoping scheme, the labels from Table II are considered as different frequencies, chosen from a set of allowed frequencies, each codeword is assigned to a particular user, and frequencies from codewords are chosen in consecutive chip time slots.

VI. OOC BASED ON AFFINE GEOMETRIES

Similarly as in MOLR or the integer lattice design case, the support sets of OOCs based on affine geometries [5] are defined as lines. The m-dimensional affine geometry, denoted as $\mathrm{AG}(m, p^s)$, over $GF(p^s)$ is a set of m-tuples, points, selected from $GF(p^{ms})$.

Let α be a primitive element of $GF(p^{ms})$. Then 0, $\alpha^0, \alpha^1, \alpha^2, \ldots, \alpha^{p^s-2}$ form all the p^{ms} points of $\mathrm{AG}(m, p^s)$. The p^{ms} m-tuples over $GF(p^s)$, representing the points in $\mathrm{AG}(m, p^s)$, form an m-dimensional vector space over $GF(p^s)$. The one-dimensional subspace of $\mathrm{AG}(m, p^s)$ is called a *line*, and the number of points in a line is given by p^s. Every point is the intersection of $(p^{ms}-1)/(p^s-1)-1$ lines. Every line

TABLE II
LATTICE 2-(21, 3, {0,1}) DESIGN

s=0	s=1	s=2	S=3	s=4	s=5	s=6
1 8 15	1 9 17	1 10 19	1 11 21	1 12 16	1 13 18	1 14 20
2 9 16	2 10 18	2 11 20	2 12 15	2 13 17	2 14 19	2 8 21
3 10 17	3 11 19	3 12 21	3 13 16	3 14 18	3 8 20	3 9 15
4 11 18	4 12 20	4 13 15	4 14 17	4 8 19	4 9 21	4 10 16
5 12 19	5 13 21	5 14 16	5 8 18	5 9 20	5 10 15	5 11 17
6 13 20	6 14 15	6 8 17	6 9 19	6 10 21	6 11 16	6 12 18

has $p^{(m-t)s}-1$ lines parallel to it. Let us define the point-line incident matrix as a bxv matrix $A=(a_{ij})$, whose columns correspond to nonorigin points and rows to lines that do not pass through the origin, whose $a_{ij}=1$ if the jth point belongs to the ith line. Each row represents a codeword. There are $b=(p^{s(m-1)}-1)(p^{sm}-1)/(p^s-1)$ different codewords of weight $k=p^s$ and length $v=p^{sm}-1$.

VII. PERFORMANCE ANALYSIS

Minimum signal-to-noise ratio (SNR) of the SAC system employing any of the BIBD class of OOCs is calculated by using the method described in [4] and [9] and is given by (3), shown at the bottom of the page, where R is the photodiode responsivity, $P_{\rm sr}$ is the effective power of a broad-band source at the receiver, e is an electron charge, B is the electrical equivalent noise bandwidth of the receiver, k_B is the Boltzmann's constant, T_r the absolute temperature of receiver noise, R_L the load resistance, Δf the optical source bandwidth, N the number of simultaneously active users, and v, k, and λ the parameters of the BIBD. The connection between BIBD parameters and three proposed OOC families are given in corresponding Sections II–IV, with $\lambda=1$. The phase-induced intensity noise, the photodiode shot noise, and the thermal noise are taken into account. The scheme capable of suppressing the MUI, shown in Fig. 1(b), is considered.

The BER can be estimated using the Gaussian approximation [2], [4]

$$P_e \leq \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\mathrm{SNR}_{\min}}{8}}\right) \tag{4}$$

where erfc(.) is the complementary error function $\mathrm{erfc}(x)=(2/\sqrt{\pi})\int_x^\infty e^{-u^2}du$.

All classes of OOCs based on BIBD can be designed to perform similarly by carefully choosing the design parameters; two such classes multifrequency-hopping (MFH) [2], [10] and modified quadratic congruence (MQC) [4], [10] were proposed recently. However, our code families have much larger flexibility in choosing the number of users. This is a consequence of the fact that in our construction, two or three parameters (p and l in MOLS, m and k in MOLR and integere lattice design, and m, p, and s in AG) can be varied, as opposed to just one free parameter (p or Q) in MQC or MFH. Moreover, our OOC construction algorithms are very simple. The performance of MOLS, MOLR, integer lattice, and AG OOC families in the presence of the phase-induced intensity noise, the photodiode shot noise, and the thermal noise are illustrated in Figs. 3–6. The system parameters are: for $\Delta\nu=3.75$ THz; $B=80$ MHz; bit-rate 155 Mb/s; central wavelength 1550 nm; $T_r=300$ K; $R_L=1030\ \Omega$; and photodiode quantum efficiency 0.6. The parameters of different BIBD families can be set in such a way that nearly identical performances are obtained, as illustrated in Figs. 3 and 6. Namely, our combinatorialy constructed codes (MOLR, integer lattice, and affine geometry designs) perform similarly to MFH codes with similar codeword weights and lengths but support a much larger number of users. For example, the integer lattice $m=18$, $k=17$ (the codeword weights are 17) supports 324 users, while an MFH with $Q=16$ (codeword weights are 17) supports 256 users. Moreover, to design MFH codes, operations are to be performed in Galois fields $(GF(Q))$, while our integer lattice design requires only simple algebraic (2). The MQC designs are restricted to a prime parameter p, while our integer lattice design supports any design for which m and k are co-prime (for example, it is enough for one parameter to be even and the other odd). Therefore, the integer lattice construction supports much more different families, which offers more flexibility in system design.

$$\mathrm{SNR}_{\min}=\frac{\frac{R^2P_{sr}^2k^2}{v^2}}{e\mathrm{BRP}_{\rm sr}\frac{k+(\lambda+1)(N-1)}{v}+\frac{BR^2P_{\rm sr}^2kN}{2v^2\Delta f}\left(\frac{N-1}{k-\lambda}+k+\lambda(N-1)\right)+\frac{4k_BT_rB}{R_L}} \tag{3}$$

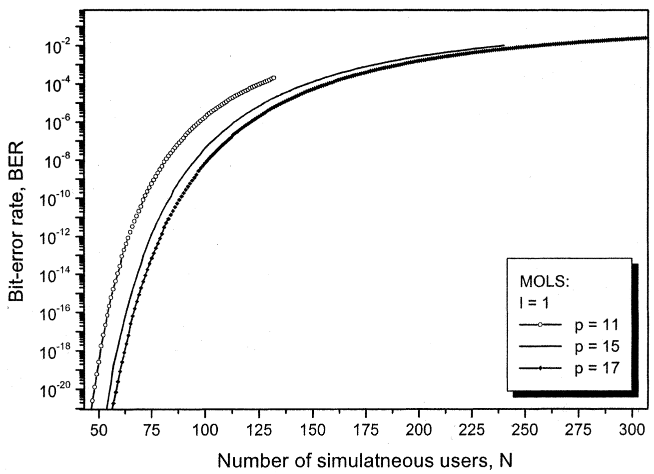

Fig. 3. BER versus number of active users for MOLS OOCs.

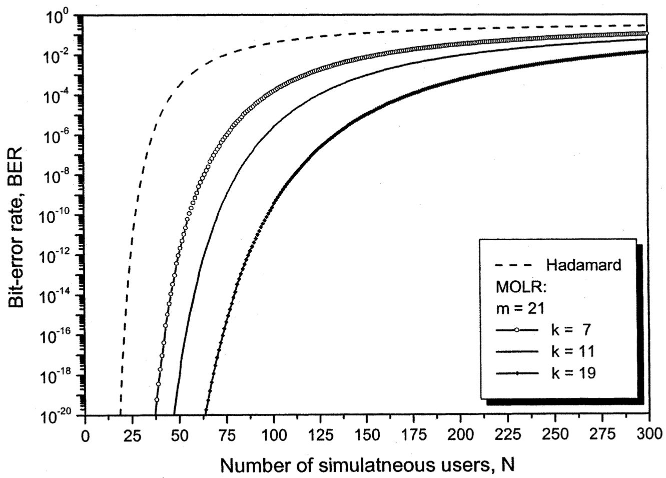

Fig. 4. MOLR OOC versus Hadamard code.

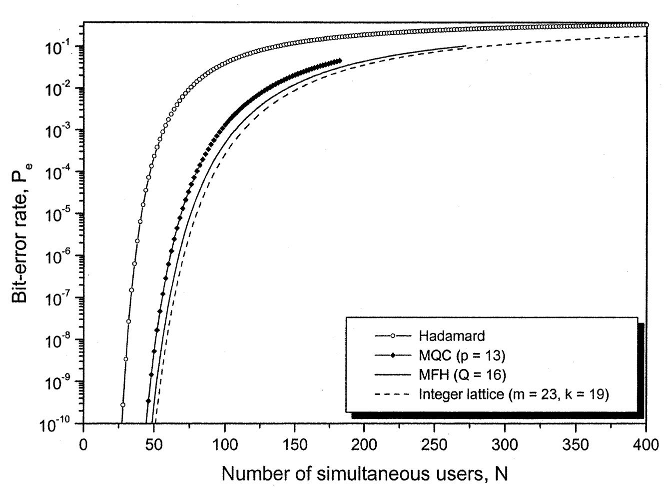

Fig. 5. BER versus number of active users for integer lattice OOCs.

The performance comparison of the MOLR-based SAC OCDMA system and Hadamard-code-based SAC system [9] [often used as a reference (see, e.g., [2] and [4])] is shown in Figs. 4 and 5. MOLR code significantly outperforms the Hadamard code.

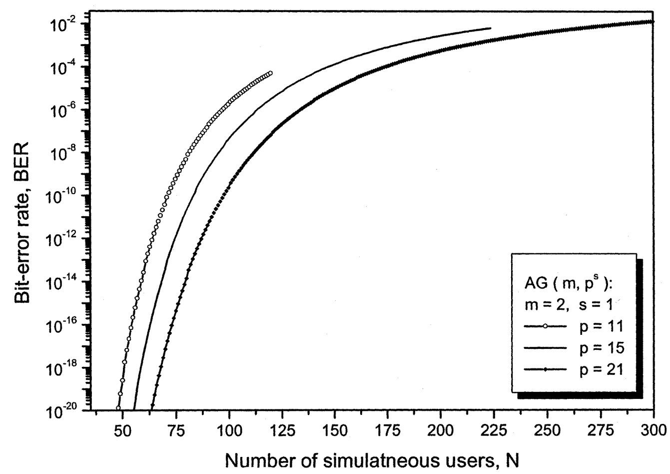

Fig. 6. BER versus number of active users for AG OOCs.

VIII. Conclusion

Three novel optical orthogonal code classes based on MOLS, MOLR, integer lattice design, and affine geometries are proposed. They are universal and can be applied to both synchronous and asynchronous incoherent OCDMA for the following classes of systems: spectral-amplitude-coding, fast-frequency-hopping schemes, and time-spreading. Our constructions offer larger flexibility in choosing the number of users than previously reported OOCs because they are described by two or three parameters that we can control (m and k in MOLR and integer lattice designs and m, p, and s in affine geometry design), while the OOC family presented in [4], for example, is given by single parameter. Moreover, our construction algorithm is very simple. In addition, arbitrary large OOC families can be constructed.

The number of spreading sequences is expressed in a closed form as a function of design parameters, and the upper bound for the BER as a function of the number of users is given. It is applicable to any class of BIBD OOC family in SAC CDMA schemes.

Spreading sequences of MOLS, integer lattice, and AG OOC families can be partitioned into parallel classes so that the sequences from different parallel classes have zero cross correlation.

A novel SAC-balanced detection decoder scheme, based on FBG technology, which is able to completely remove the MUI for the proposed unipolar codes families is also proposed.

References

[1] J. A. Salehi, "Code division multiple-access techniques in optical fiber networks—Part I: Fundamental principles," *IEEE Trans. Commun.*, vol. 37, pp. 824–833, Aug. 1989.
[2] Z. Wei and H. Ghafouri-Shiraz, "Proposal of a novel code for spectral amplitude-coding optical CDMA systems," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 414–416, Mar. 2002.
[3] F. R. K. Chung, J. A. Salehi, and V. K. Wei, "Optical orthogonal codes: Design, analysis, and applications," *IEEE Trans. Inform. Theory*, vol. 35, pp. 595–604, May 1989.
[4] Z. Wei, H. M. H. Shalaby, and H. Ghafouri-Shiraz, "Modified quadratic congruence codes for fiber Bragg-grating-based spectral-amplitude-coding optical CDMA systems," *J. Lightwave Technol.*, vol. 19, pp. 1274–1281, Sept. 2001.

[5] I. Andersen, *Combinatorial Designs: Construction Methods*. New York: Wiley, 1990.

[6] K. Kamakura and I. Sasase, "A new modulation scheme using asymmetric error-correcting codes embedded in optical orthogonal codes for optical CDMA," *J. Lightwave Technol.*, vol. 19, pp. 1839–1850, Dec. 2001.

[7] S. Kim, K. Yu, and N. Park, "A new family of space/wavelength/time spread three-dimensional optical code for OCDMA networks," *J. Lightwave Technol.*, vol. 18, pp. 502–511, Apr. 2000.

[8] H. Fathallah, L. A. Rusch, and S. LaRochelle, "Passive optical fast frequency-hop CDMA communication system," *J. Lightwave Technol.*, vol. 17, pp. 397–405, Mar. 1999.

[9] E. D. J. Smith, R. J. Blaikie, and D. P. Taylor, "Performance enhancement of spectral-amplitude-coding optical CDMA using pulse-position modulation," *IEEE Trans. Commun.*, vol. 46, pp. 1176–1185, Sept. 1998.

[10] Z. Wei and H. Ghafouri-Shiraz, "Unipolar codes with ideal in-phase cross-correlation for spectral amplitude-coding optical CDMA systems," *IEEE Trans. Commun.*, vol. 50, pp. 1209–1212, Aug. 2002.

Ivan B. Djordjevic received the B.Sc., M.Sc., and Ph.D. degrees, all in electrical engineering, from the University of Nish, Serbia.

From 1994 to 1996, he was with the University of Nish, Nish, Serbia. From 1996 to 2000, he was with the State Telecommunications Company, District Office for Networks-Nish, Serbia, where he was involved in digital transmission systems commissioning and acceptance, design, maintenance, installation, and connection. From 2000 to 2001, he was with the National Technical University of Athens, Greece, and with TyCom US, Inc. (now TyCo Telecommunications). He was involved in modeling and simulation of dense-wavelength-division-multiplexing (DWMD) systems. In 2002, he was with the University of Arizona, Tucson, working on forward-error correction and iterative decoding for long-haul transmission. He is now with the University of Bristol, Bristol, U.K. He is the author of more than 30 international journal articles and more than 40 international conference papers. His research interests include DWDM fiber-optic communication systems and networks, coding for optical communications, optical CDMA, coherent optical communications, information theory, and statistical communication theory.

Bane Vasic (S'92–M'93–SM'02) received the B.Sc., M.Sc., and Ph.D. degrees, all in electrical engineering, from the University of Nish, Nish, Serbia.

From 1996 to 1997, he worked as a Visiting Scientist at the Rochester Institute of Technology and Kodak Research, Rochester, NY, where he was involved in research in optical storage channels. From 1998 to 2000, he was with Lucent Technologies, Bell Laboratories. He was involved in research in read channel architectures and iterative decoding and low-density parity check codes, as well as development of codes and detectors for five generations of Lucent (now Agere) read channel chips. Presently, he is a Faculty Member of the Electrical and Computer Engineering Department, University of Arizona, Tucson. He has authored more than 15 journal articles and more than 50 conference articles. His research interests include coding theory, information theory, communication theory, and digital communications and recording.

Dr. Vasic is a Member of the Editorial Board of the IEEE TRANSACTIONS ON MAGNETICS. He serves as the Technical Program Chair, IEEE Communication Theory Workshop, 2003, and as Co-Organizer of the Center for Discrete Mathematics and Theoretical Computer Science (DIMACS) Workshop on Optical/Magnetic Recording and Optical Transmission, 2003.