Design of Multiweight Unipolar Codes for Multimedia Optical CDMA Applications Based on Pairwise Balanced Designs

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***Abstract*—A novel class of constant-length variable-weight optical orthogonal codes is proposed that can support multimedia services with different data rates and quality-of-service requirements. The construction is based on the pairwise balanced designs, or more specifically, on an incidence structure defined on an integer lattice. Proposed codes are suitable for spectral-amplitude coding, fast-frequency hopping, and time-spreading encoding in multimedia environment. A novel dual-balanced decoder is proposed capable of canceling multiuser interference in multimedia applications for spectral-amplitude-coding schemes employing the unipolar codes having nonfixed in-phase cross correlation.**

***Index Terms*—Multimedia, optical code-division multiple access (OCDMA), optical orthogonal codes (OOCs), pairwise balanced designs.**

I. INTRODUCTION

OPTICAL code-division multiple access (OCDMA) offers several attractive features like asynchronous access, privacy and security in transmission, ability to support variable bit rate and bursty traffic, and scalability of the network, [1]–[7]. Since code-division mutliple-access (CDMA) systems can support asynchronous bursty traffic, transparency to overlaid protocols, and decentralized operations, they are suitable for local area networks (LANs) and possibly metropolitan area networks (MANs).

Discrimination of an unwanted signal is achieved by assigning minimally interfering codes (also known as address sequences or signature sequences) to each user, selected from a family of so-called optical orthogonal codes (OOCs). To support data-format-independent, data-rate-independent, as well as time-transparent transmission in multimedia applications, novel classes of OOCs are required. Conventional OOC families are designed to support constant-bit-rate applications [1]–[7]. When such codes are used to support the variable-bit-rate or multiple-bit-rate multimedia applications, their predetermined cross correlation valid under fixed weight and code lengths, due to unequal or changeable codeword lengths, can be violated. To avoid such situations, several novel classes of OOCs were recently proposed [12]–[15].

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In this paper, a novel constant-length variable-weight class of OOCs is proposed. The construction is based on combinatorial designs, more specifically on pairwise balanced designs (PBD). Three different constructions of novel OOC families are discussed, namely: 1) the method of adjoining elements; 2) the method of removing elements; and 3) difference-systems-based constructions. Those PBD OOC families are able to support up to four different services. We also propose an algorithm for constructing PBD OOCs from resolvable balanced incomplete block designs (BIBDs) supporting many arbitrary different services. The algorithm is illustrated on our novel combinatorial construction—the integer lattice construction. This construction can be applied to both synchronous and asynchronous applications, and it is compatible with spectral-amplitude-coding (SAC), fast-frequency-hopping, and time-spreading-encoding schemes. The novel SAC dual-balanced detection scheme capable of suppressing the multiuser interference in multimedia environment, when sequences having non-fixed in-phase cross correlation are employed, is proposed, as well. To our best knowledge, there is no published work on spectral amplitude coding for multimedia applications.

II. SYSTEM DESCRIPTION AND PROBLEM STATEMENT

The simplest OCDMA network consists of N transmitter/receiver pairs connected in a star configuration [1]. To send the information from ith to jth user, the address code for the receiver j is impressed upon data by the encoder at the ith node. In distribution and broadcasting applications, the fixed-transmitter assignment is adopted so that the ith codeword is assigned to the ith transmitter in the network. Such a system should be able to accommodate a variety of services, including multirate data, images, graphics, audio, and video with different performance and traffic constraints and different qualities of service (QoS). For example, errors cannot be tolerated for high-speed data transmission, while voice terminals can tolerate some transmission errors while having stringent delay requirements. However, the real-time video applications require both error-free transmission and real-time delivery.

In order to meet these requirements, several classes of codes are proposed recently; variable-length [14] and double-weight codes [12] are two main categories and can be combined into a multirate scheme using so-called power control method described in [11]. A multicode CDMA technique [14], proposed for wireless communications, can be applied in optical systems as well. This technique allocates multiple codes to high-rate services, and each user employs multiple sequences for transmission. The main idea behind multilength codes constuction is to use short codewords to construct longer, while maintaining the correlation properties. Two classes of double-weight two-dimensional (2-D) OOC-based on the Galois field theory were proposed in [12], and the upper bound of the cardinality on multiweight 2-D codes is established as well. Unfortunately, the proposed OOCs are able to support only two different services, and no performance is demonstrated.

We propose novel construction of a variable-weight OOC able to support more than two different services. The construction is based on combinatorial designs, more precisely, on the PBDs.

III. PBD-Based OOC Constructions

In general, in combinatorics, a design is a pair (V, B), where V is a set of some elements called *points*, and B is a collection of subsets of V called *blocks*. The numbers of points and blocks are denoted by $v = |V|$ and $b = |B|$, respectively. If $t \leq v$ is an integer parameter, such that any subset of t points from V is contained in exactly λ blocks, we deal with a t-design. A BIBD is a two-design for which each block contains the same number of points k, and every point is contained in the same number of blocks r. A BIBD is resolvable if there exists a nontrivial partition of its blocks set B into parallel classes, each of which partitions the point set V. The BIBD is denoted by either $\mathrm{BIBD}(v, k, \lambda)$ or $\mathrm{BIBD}(v, b, r, k, \lambda)$.

A PBD $\mathrm{PBD}(v, K, \lambda)$ is a collection of subsets (blocks) of a v set V with the size of each block in K, less than v, and each pair of elements (points) occurs together in exactly λ of the blocks. Clearly, for $K = \{k\}$ the concept of a PBD reduces to that of a BIBD. For example, blocks {1,2,3,4}, {1,5,6,7}, {1,8,9,10}, {2,5,8}, {2,6,9}, {2,7,10}, {3,5,10}, {3,6,8}, {3,7,9}, {4,5,9}, {4,6,10}, {4,7,8} form a $\mathrm{PBD}(10, \{3, 4\}, 1)$. The points describe the positions of "1"s in corresponding codewords. For example, the codewords corresponding to the first and to the last blocks are (1 1 1 1 0 0 0 0 0 0) and (0 0 0 1 0 0 1 1 0 0). The blocks {1,2,3,4,5}, {1,6,7,8,9}, {1,10,11,12,13}, {2,6,10,14}, {2,7,11,15}, {3,6,12,15}, {3,7,13,14}, {4,8,10,15}, {4,9,11,14}, {5,8,12,14}, {5,9,13,15}, {1,14,15}, {2,8,13}, {2,9,12}, {3,8,11}, {3,9,10}, {4,6,13}, {4,7,12}, {5,6,11}, and {5,7,10} are the blocks of a $\mathrm{PBD}(15, \{3, 4, 5\}, 1)$. Again, the labels in the blocks denote the position of "1"s in corresponding codewords. The second example is applicable to the synchronous OCDMA system that supports three different services with three sequences of weight 5, eight sequences of weight 4, and nine sequences of weight 3.

If a $\mathrm{PBD}(v, K, \lambda)$ exists with b_i blocks of size k_i for each $k_i \in K$, then the following useful expression that connects PBD parameters with number of blocks of different sizes is easy to prove:

$$\lambda v\,(v-1) = \sum_i b_i k_i\,(k_i - 1). \tag{3}$$

Now, we address the problem of constructing PBDs from BIBDs.

A. Adjoining-Elements Method

If a $\mathrm{BIBD}(v, k, \lambda)$ is a resolvable design, then by adding a new symbol θ_i to each block of the ith resolvability class ($i = 1, 2, \ldots, x$; $1 < x \leq r$) and adding a new block $\{\theta_1, \theta_2, \ldots, \theta_x\}$, we get a $\mathrm{PBD}(v + x, \{k + 1, k, x\}, 1)$ if $x < r$ and a $\mathrm{PBD}(v + r, \{k + 1, r\}, 1)$ if $x = r$. For example, the blocks of a $\mathrm{BIBD}(9, 3, 1)$ can be grouped into the following resolution (parallel) classes, with labels denoting the positions of "1"s within the codewords:

$$\begin{matrix} \{1,2,3\} & \{1,5,8\} & \{1,4,7\} & \{1,6,9\} \\ \{4,8,9\} & \{3,4,6\} & \{2,6,8\} & \{2,4,5\} \\ \{5,6,7\} & \{2,7,9\} & \{3,5,9\} & \{3,7,8\} \end{matrix}.$$

By adding θ_1 to each block of the first resolution class, adding θ_2 to the second, and adding a block $\{\theta_1, \theta_2\}$, we get a $\mathrm{PBD}(11, \{2, 3, 4\}, 1)$, as follows:

$$\begin{matrix} \{1,2,3,\theta_1\} & \{1,5,8,\theta_2\} & \{1,4,7\} & \{1,6,9\} & \{\theta_1,\theta_2\} \\ \{4,8,9,\theta_1\} & \{3,4,6,\theta_2\} & \{2,6,8\} & \{2,4,5\} & \\ \{5,6,7,\theta_1\} & \{2,7,9,\theta_2\} & \{3,5,9\} & \{3,7,8\} & \end{matrix}$$

in which θ_1 and θ_2 are considered as tenth and eleventh positions of "1"s in corresponding codewords.

PBD can be designed using the method of adjoining elements based on the group-divisible designs (GDDs) [8]–[10]. A GDD with parameters $v = mn$, b, r, k, $\lambda_1 = 0$, $\lambda_2 = 1$ is denoted by $\mathrm{GDD}(v, k, n, 0, 1)$. From resolvable $\mathrm{GDD}(v, k, n, 0, 1)$, we are able to construct $\mathrm{PBD}(v + x, \{k + 1, k, n, x\}, 1)$ if $1 < x < r$, $\mathrm{PBD}(v + x, \{k + 1, n, r\}, 1)$ if $x = r$, and $\mathrm{PBD}(v + 1, \{k + 1, k, n\}, 1)$.

B. Difference-Systems-Based Constructions

If $D_1, D_2, \ldots, D_{\mathrm{t}}$ are sets of size k in an additive abelian group G of order v such that differences arising from D_i give each nonzero element of G exactly λ times, then $D_1, D_2, \ldots, D_{\mathrm{t}}$ are said to form a (v, k, λ) difference system in G. It can be shown [8] that sets $D_i + g_j$, $g_j \in G = \{g_0, g_1, \ldots, g_{v-1}\}$, $1 \leq i \leq t$, $0 \leq j \leq v - 1$ form blocks of $\mathrm{BIBD}(v, vt, kt, k, \lambda)$.

Difference systems yield block designs because the sets of a difference system possess two properties: 1) they are all of the same size, and 2) they give every nonzero element as a difference between them exactly the same number of times (λ). When the sets are permitted to be of different sizes, but the balanced property is being held, the method yields PBDs.

For example, the sets {0,1,3,7,25,38}, {0,5,20,32,46,75}, and {0,8,17,47,57} yield a $\mathrm{PBD}(90, \{5, 6\}, 1)$, with positions of "1"s in corresponding codewords denoted from 0 to 89.

C. Removing-Elements Method

This is the simplest possible method of constructing PBDs from BIBD, and the main idea is to remove some elements from a BIBD. For example, if we start with $\mathrm{BIBD}(7, 3, 1)$ having blocks (codewords) {1,2,4}, {1,3,7}, {1,6,5}, {2,5,3}, {2,6,7}, {3,6,4}, and {4,7,5}, and remove point 4 from all blocks containing it, we get a $\mathrm{PBD}\{6, \{2, 3\}1\}$ having {1,2}, {1,3,7}, {1,6,5}, {2,5,3}, {2,6,7}, {3,6}, and {7,5} blocks.

Therefore, if a $\mathrm{BIBD}(v,k,\lambda)$ exists, then by omitting one symbol we get a $\mathrm{PBD}(v-1,\{k-1,k\},1)$. Further, by omitting x ($2 \le x \le k$) symbols occurring in the same block, we get a $\mathrm{PBD}(v-x,\{k-x,k-1,k\},1)$. We can also note that by omitting three symbols not occurring in the same block, we get a $\mathrm{PBD}(v-3,\{k-2,k-1,k\},1)$.

The methods proposed so far (e.g., [12]) are able to support two different multimedia services only, as their OOC families contain the codewords of only two different weights. The methods (a), (b), and (c) are able to support at most four different services. For a larger number of service, we are proposing the following approach. Denote with $B=(b_{ij})$ the block-point matrix of the first resolvability class of a BIBD, with b_{ij} ($1 \le i \le m$, $1 \le j \le k$, m—the number of blocks in the resolvability class) being the points of the ith block. Let $\beta = [\beta_1 \beta_2 \ldots \beta_k]$ be the "population vector" with elements denoting the percentage of points from the jth ($1 \le j \le k$) column remaining undeleted. $\beta = [11 \ldots 1]$ means that all points from initial BIBD remained undeleted. Delete the last $\lfloor m(1-\beta_j) \rfloor$($\lfloor x \rfloor$ is denoted an integer part of a real number x) points from the jth ($1 \le j \le k$) column and renumerate the remaining points.

The algorithm can be used on any resolvable BIBD.

In the remainder of the paper, we present a novel construction of OOC codes and then demonstrate our proposal to construct sequences of different weights.

IV. Integer Lattice Construction OOC

Consider a subset of a rectangular integer lattice shown in Fig. 1. 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, $0 \le s \le m-1$, starting at the point (x,a), contains the points $\{(x, a+sx \bmod m) : 0 \le x \le k-1\}$, where $0 \le s \le m-1$. 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/asynchronous CDMA applications, we give an example of a small lattice of dimensions $m=5$ by $k=4$ shown in Fig. 1. The lines of slopes $0 \le s < 5$ form a 2-(20,4,{0,1}) design, which is a support set of an OOC family with codeword weight $k=4$. In other words, each line of a design specifies positions of nonzero elements in a codeword, and the resulting design is given in Table I. The columns correspond to the lines of different slopes in Fig. 1. For example, the line of slope 3 starting at (0,0) in Fig. 1 contains the points {1, 9, 12, 20}. The labels denote the positions of "1"s within a codeword.

The integer lattice construction with vertical and horizontal dimensions being 7 and 5, respectively, and population vector $[1 \quad 0.8 \quad 0.5 \quad 0.8 \quad 0.7]$ yields to the OOC family having 14 users of weight 5, 23 users of weight 4, 11 users of weight 3, and one user of weight 1. The multiweight OOC codewords are given in Table II, the labels being the positions of "1"s within a codeword. Namely, the population vector indicates that the last point in the second column ($\lfloor m(1-\beta_2) \rfloor = \lfloor 7(1-0.8) \rfloor = 1$), the last three points in the third, the last point in the fourth, and the last two points in the fifth column of the point-block incident matrix of the initial design, corresponding to the lines of slope $s=0$, are to be removed. After renumeration of the remained points, the resulting design in Table II is obtained.

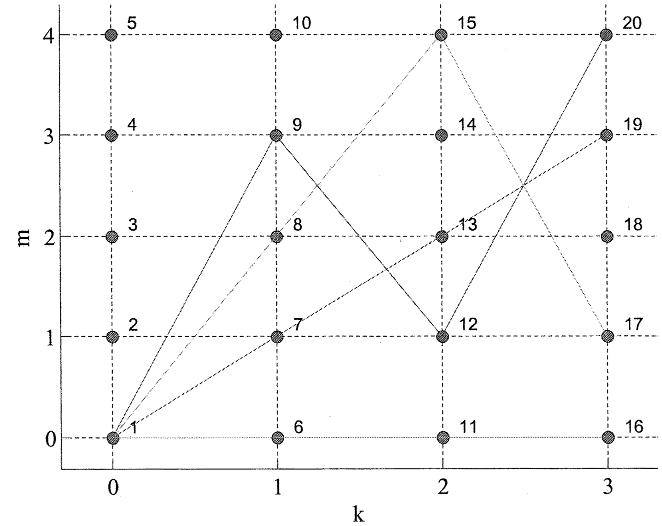


Fig. 1. Example of the integer rectangular lattice for $m=5$ and $k=4$.

The integer lattice PBD can be applied to the spectral-amplitude coding, fast frequency hopping, and time-spreading encoding. For the frequency-hopping scheme, the labels in Table II should be considered as different frequencies, chosen from a set of allowed frequencies, so that each codeword is assigned to a particular user, and the frequencies from codewords are chosen in consecutive chip time slots. With at most one hit per chip, the design cardinality is m^2, and there are $mk - \sum_{i=1}^{k} \lfloor m(1-\beta_i) \rfloor$ frequencies in a set and k chips within a bit interval. The integer lattice-based PBD family (given in Table II) is composed of codewords having the in-phase cross correlation of either 0 or 1. The existing balanced detection schemes for SAC systems [4] require OOC sequences having fixed in-phase cross correlation. We propose a dual-balanced detection fiber Bragg grating (FBG) scheme (Fig. 2) capable of canceling the multiuser interference for SAC systems employing the OOCs that do not have the fixed in-phase cross correlations. In our dual-balanced decoding scheme, the signal at the upper balanced detector output is proportional to $R_{x,y} - R_{\bar{x},y}$ (with x being the desired sequence, and y the interefering sequence), and the signal at the lower one is proportional to $R_{x,x} + R_{x,y} - R_{\bar{x},y}$. From Fig. 2, it can be seen that the multiuser interface (MUI) is completely removed with dual-balanced detection. Since our decoding scheme does not require sequences having fixed in-phase cross correlation, for a given codeword length, the OOC families having larger cardinality may be constructed.

A. Asynchronous Time-Spreading Encoding

For time-spreading encoding (e.g., Table II), the proposed design supports m users with codeword weights at most k and codeword lengths $mk - \sum_{i=1}^{k} \lfloor m(1-\beta_i) \rfloor$. Each row may be viewed as an $\mathrm{OOC}(mk - \sum_{i=1}^{k} \lfloor m(1-\beta_i) \rfloor, k, 2)$ family. (The first parameter is the codeword length, the second

TABLE I
LATTICE 2-(20, 4, {0,1}) DESIGN

s=0	s=1	s=2	s=3	s=4
1 6 11 16	1 7 13 19	1 8 15 17	1 9 12 20	1 10 14 18
2 7 12 17	2 8 14 20	2 9 11 18	2 10 13 16	2 6 15 19
3 8 13 18	3 9 15 16	3 10 12 19	3 6 14 17	3 7 11 20
4 9 14 19	4 10 11 17	4 6 13 20	4 7 15 18	4 8 12 16
5 10 15 20	5 6 12 18	5 7 14 16	5 8 11 19	5 9 13 17

TABLE II
LATTICE 2-(28, {1,3,4,5},{0,1}) PBD DESIGN

s=0	s=1	s=2	s=3	s=4	s=5	s=6
1 8 14 18 24	1 9 16 21 28	1 10 25	1 11 20	1 12 15 23 26	1 13 17 19	1 22 27
2 9 15 19 25	2 10 17 22	2 11 18 26	2 12 14 21	2 13 16 27	2 20 24	2 8 23 28
3 10 16 20 26	3 11 23	3 12 19 27	3 13 15 22 24	3 17 18 28	3 8 21 25	3 9 14
4 11 17 21 27	4 12 24	4 13 14 20 28	4 16 23 25	4 8 19	4 9 22 26	4 10 15 18
5 12 22 28	5 13 18 25	5 15 21	5 8 17 26	5 9 20	5 10 14 23 27	5 11 16 19 24
6 13 23	6 14 19 26	6 8 16 22	6 9 18 27	6 10 21 24	6 11 15 28	6 12 17 20 25
7	7 8 15 20 27	7 9 17 23 24	7 10 19 28	7 11 14 22 25	7 12 16 18	7 13 21 26

is the maximum codeword weight, and the third one defines the maximum cross-correlation value). If all sequences in a design are employed, the design supports m^2 users with the codeword length $mk - \sum_{i=1}^{k} \lfloor m(1-\beta_i) \rfloor$ and maximum codeword weight k, respectively, but the cross-correlation property becomes degraded. Notice that in terms of the average cross correlation, the design given in Table II belongs to the OOC$(mk - \sum_{i=1}^{k} \lfloor m(1-\beta_i) \rfloor, k, 1)$ class. The system outperforms previously reported ones [16], [19], and the OOC cardinality is significantly larger. For example, for single-weight OOC of length 1071 and weight 9, the truncated Costas OOC from [16] supports only six users, while the integer lattice supports 119 users of the first type, and 119^2 users of the second type. The construction given in [19] supports only two different services and has worsened the cross-correlation constraint (3). Our construction has the cross-correlation constraint equal to two, performs much better (see Fig. 4), and supports a much higher number of users. It can also support many arbitrary different services. (As outlined in [16], the real significance of the Johnson bound is questionable and comparison with respect to the Johnson bound is omitted.)

The results for the integer lattice single-weight OOC family for the population vector $[1 \quad \ldots \quad 1]$ and complete single-weight family (in an asynchronous environment) are shown in Fig. 3. The comparable performance with previously reported OOC families [16] was found, while larger OOC families can be constructed using the integer lattice construction [1]. For the number of users larger than 20, in either case, some kind of error control coding or MUI cancellation scheme [17] is to be employed to deal with MUI.

The performance of the multiple-weight integer lattice OOC is illustrated in Fig. 4 for $m = 33$ and $k = 27$, the asynchronous transmission, and the worst case scenario chip-synchronous case [1]. For the population vector $[1 \quad 0.7 \quad \ldots \quad 0.7]$ [Fig. 4(a)], up to 11 different services can be supported with the codeword length 657. For the population vector $[1 \quad 0.6 \quad \ldots \quad 0.6]$ [Fig. 4(b)], up to 15 services can be supported with the codeword length 553. Therefore, many different multiweight classes can be generated by changing the population vector. (In the calculation, an equal fraction of sequences from different services is assumed.)

The performance is evaluated using the method of averaging the cross correlation and expression (23) from [18], with no power control, since overlapping results with the exact expressions were demonstrated [18]. The same method of performance calculation was applied in [19].

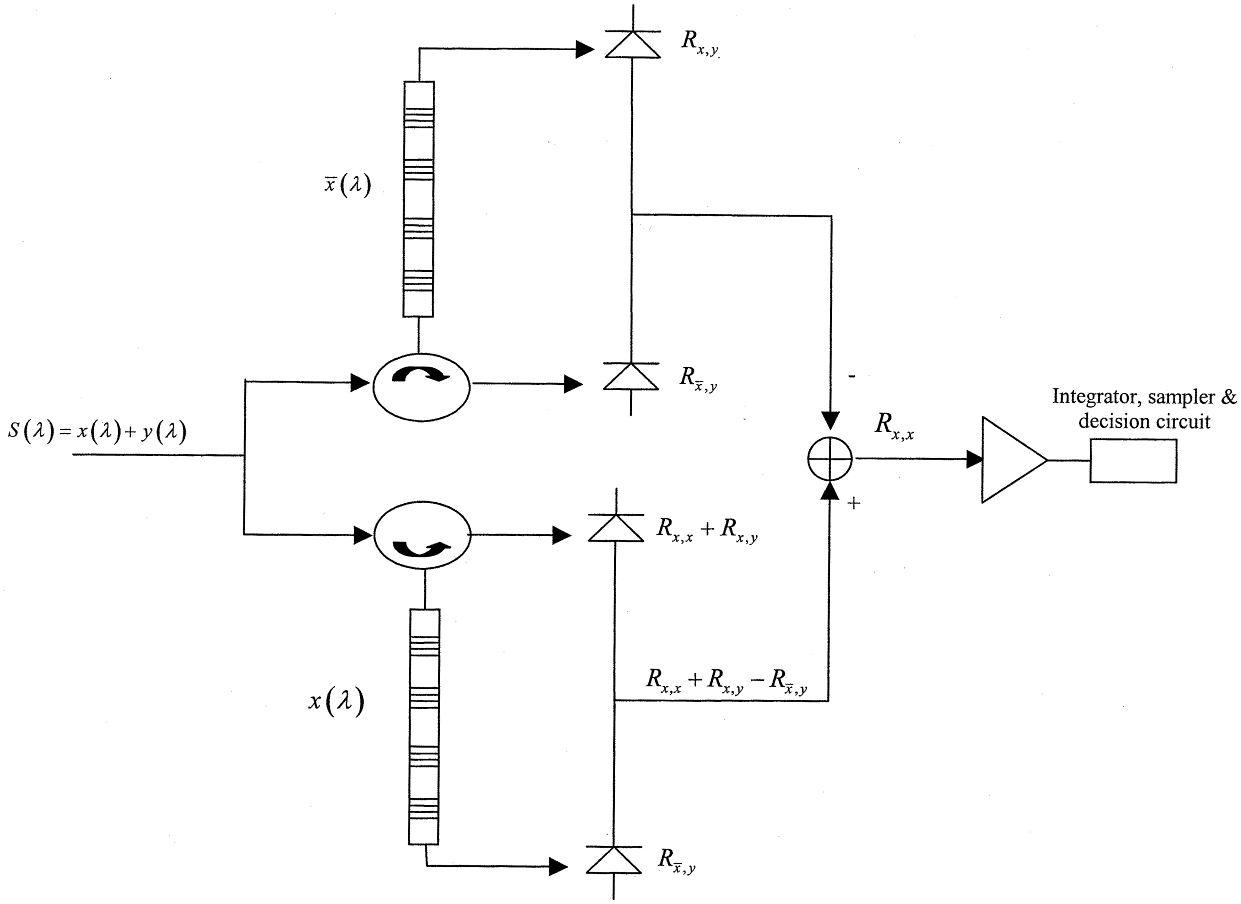


Fig. 2. Dual-balanced MUI cancellation decoder for SAC schemes.

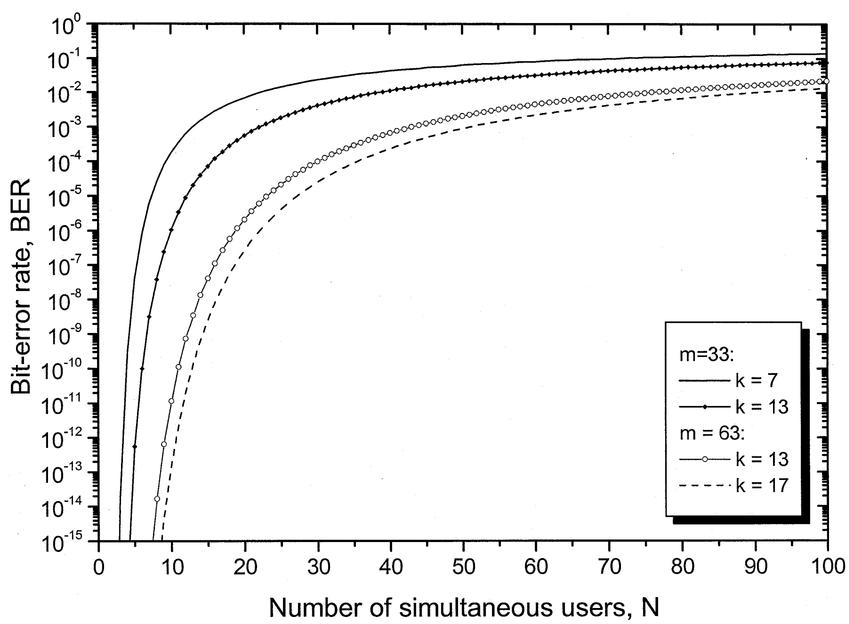
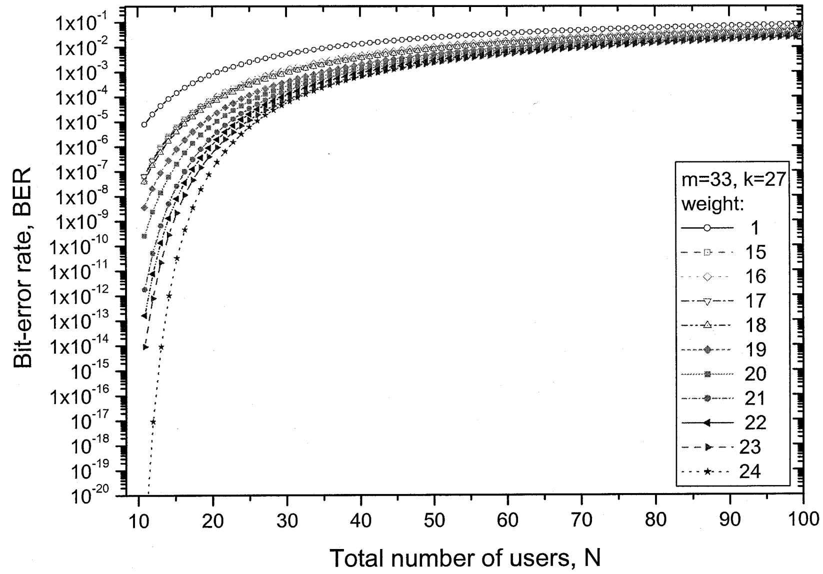


Fig. 3. Single-weight OOC family bit-error rate (BER).

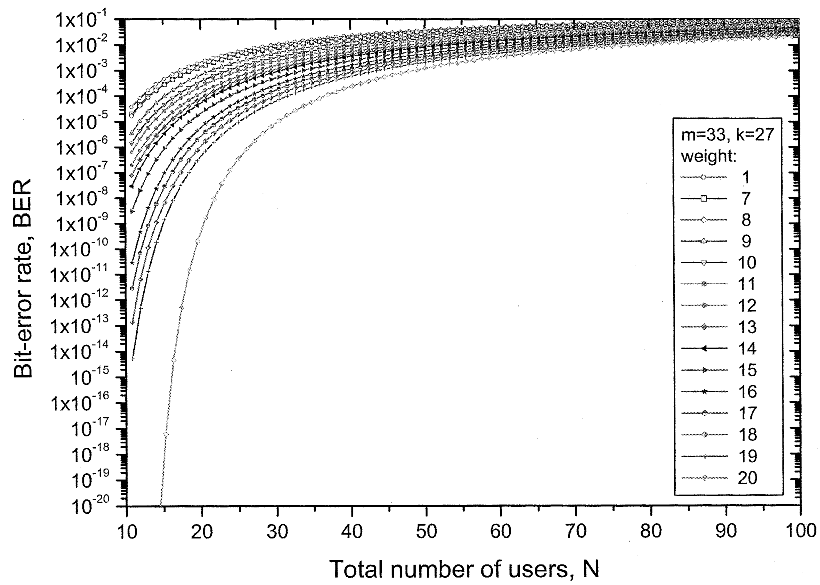
Using the algorithm similar to that proposed in [14] and our PBD constructions, it is possible to design sequences with both different lengths and weights, which remains for further research.

V. Conclusion

A novel class of constant-length variable-weight OOCs suitable to support multimedia services with different data rates



(a)



(b)

Fig. 4. BER versus total number of users for different codeword weights: (a) population vector $[1\ \ 0.7\ \ \ldots\ \ 0.7]$ and (b) population vector $[1\ \ 0.6\ \ \ldots\ \ 0.6]$.

and QoS requirements has been proposed in this paper. The construction is based on the PBDs. The construction algorithm is simple, and it is illustrated on our novel construction of the OOC—the integer lattice. By relaxing the cross-correlation constraints, many large families can be constructed with comparable performance to codes designed using strict correlation constraints (e.g., [16]). Namely, the previous constructions mainly have fixed in-phase cross correlation. In integer lattice construction, the codewords have in-phase cross correlation 0 or 1, many codewords are orthogonal to each other, which enables the larger families to be constructed while still satisfying performance in the presence of MUI. By changing the population vector, many different multiweight OOC families can be constructed. The integer-lattice-construction-based PBD is applicable to spectral-amplitude-coding, fast-frequency-hopping, and time-spreading-encoding OCDMA schemes. The novel dual-balanced detection FBG scheme that is proposed is capable of canceling the MUI in a multimedia environment in a SAC scheme employing sequences having the nonfixed in-phase cross correlation.

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