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One-Dimensional Unipolar Orthogonal Codes and their Clique Set Formation: A Survey

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***Abstract*— The one dimensional unipolar orthogonal codes are employed as signature sequences in spread spectrum modulation schemes like incoherent optical CDMA system. The cardinality or upper bound of code set, containing one dimensional unipolar orthogonal codes of code length 'n' and code weight 'w' and correlation constraint λ , is given by Johnson bounds. Conventionally these codes are represented by weighted position representation (WPR) or position of bit '1's in the code. The auto-correlation and cross-correlation constraints of the unipolar orthogonal codes are calculated using the binary sequences equivalent to these codes in WPR. Two other representations of one dimensional unipolar orthogonal codes are proposed as well as two methods for calculation of correlation constraints of these unipolar orthogonal codes. This paper proposes an algorithm to search a family of multiple sets of minimum correlated one dimensional unipolar (optical) orthogonal codes (1-DUOC) or optical orthogonal codes (OOC) with fixed as well as variable code parameters. The cardinality of each set is equal to upper bound. The codes within a set can be searched for general values of code length 'n', code weight 'w', auto-correlation constraint less than or equal to λ_a , and cross-correlation constraint less than or equal to λ_c , such that n>>w>>(λ_a,λ_c). Each set forms a maximal clique of the codes within given range of correlation properties (λ_a,λ_c).**

***Index Terms*— Difference of positions representation (DoPR), fixed weighted positions representation (FWPR), one dimensional unipolar orthogonal codes (1-D UOC)**

I. INTRODUCTION

Every day better ideas are being implemented to fulfill the basic desire of people to have better communication medium. Now-a-days, the common mediums for communication are Internet, telephone (mobile phone), television and AM/FM radio. These mediums of communication are either wired or wireless i.e. the transmitters and the receivers are connected with each other through cable (wires) or through a wireless medium. The wireless medium may be atmosphere or tropospheric layers which reflects the radio waves with limited bandwidth (Mega-Hertz range) and power. The other mediums providing wireless communication are based on human made satellites which can provide faster communication limited up to few Mbps through stations or towers on earth.

Similarly, in Optical CDMA multiple sets of minimum correlated one-dimensional uni-polar (optical) orthogonal codes with fixed or variable code parameters are required to increase the channel capacity and inherent security. The code parameters for one dimensional unipolar orthogonal codes are code length *'n'*, code weight *'w'*, auto-correlation constraint λ_a and cross-correlation constraint λ_c such that n>>w>(λ_a,λ_{ca}). Various one-dimensional optical orthogonal code design schemes for constant weight have been proposed in literature. These schemes can design single set of optical orthogonal codes corresponding to specific values of code parameters (n,w, λ_a,λ_c). The sets of 1-DUOC with variable or multi-weight parameter have larger cardinality than that of the set with constant code weight parameter. The set of codes with low code weights provide poor BER performance, then the set of codes with large code-weights are desirable. The set of codes having subsets with different code weight parameters can provide multiple QoS (quality of service) as per the need. The sets of 1-DUOC or OOC with variable or multi code-length parameter can be used for multi-rate systems employing OOC. The 1-DUOC with multi-length and multi-weight provide the multi-class set of 1-DUOC with larger cardinality and inherent security for use in multi-rate systems. The general values or unspecified parameters of the codes increase the inherent security of the system by decreasing the probability of generating same set of signature sequences (pattern) or orthogonal codes, unless code parameters are known. It can be said that the sets of 1-DUOC or OOC with general and variable code parameters are needed for systems incorporating OOC for better performance.

We have designed the single family of minimum correlated multiple sets for fixed code parameters through proposed maximal clique search method. Secondly two or more such families can be found for various length and weight parameters. Finally one set from each family is searched such that it has minimum correlation with all others. These finally searched minimum correlated maximal clique sets of orthogonal codes with multi-length and multi-weight parameters even with equal or unequal values of auto-correlation constraint and cross-correlation constraint can be put in other family. The auto-correlation constraint for the set of codes designed here is never greater than two. The cross-correlation constraint for set of codes is always equal to one but this may exceeds to two for multiple sets of codes with fixed or variable code parameters representing tradeoff between larger cardinality and better BER performances. Each set has maximum number of codes which is given by upper bound of the set such that the codes within every set form a maximal clique. In graph theory, a clique is a sub-graph such that each pair of nodes in the sub-graph is connected or adjacent. We can represent all codes as nodes and a link exist between two nodes if cross-correlation is less than or equal to λ_c . A sub-set of codes where each possible pair of codes has a link between them is the clique set.

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II. LITERATURE REVIEW

The advantages of CDMA (code division multiple access) system over other multiple access systems are well known to researchers in the field of communication. These advantages forced them to think to access the optical fiber bandwidth using code division multiplexing in optical domain. The Optical CDMA has come across a lot of hurdles and challenges from its inception. The wireless CDMA system requires bipolar orthogonal codes for spread spectrum modulation with binary information of multiple users. But the optical fiber could process only unipolar codes while transmitting the multiplexed information. The design of optical transmitter and optical receiver for CDMA system were big challenges along-with the design of uni-polar orthogonal codes. The researchers accepted the challenges to take advantages of CDMA system to access huge bandwidth of optical fibers.

In 1986, Fan, Prucnal and Santoro[1] gave a basic idea to spread spectrum fiber-optic local area network using optical processing.

In 1988, Gagliardi, Khansefid with Taylor proposed a new design of binary sequence sets for pulse coded system [2]. In 1988, Foschini and Vannucci gave the concept of using spread spectrum for making a high capacity fiber optic local area network [3].

In 1989, Salehi. J presented fundamental principles for code division multiple access techniques in optical fiber networks [4]. In 1989, Kiasaleh. K proposed the spread spectrum optical on-off keying communication system [5]. At the end of this year Kwong, Prucnal, and Perrier gave detailed comparison of synchronous versus asynchronous CDMA for fiber-optic LANs using optical signal processing [6].

In 1996, Gagliardi and Mendez gave the performance improvement of optical communications with hybrid WDM and CDMA [11]. In 2002, Sergeant and Stok, described the role of optical CDMA in access network telling merits and demerits of optical CDMA system which makes new challenges in the field of optical CDMA systems [12].

It was a big milestone in this field, with the realities of optical CDMA systems about their physical realization. The work for design of one dimensional unipolar (optical) orthogonal codes started with the advent of spread spectrum multiplexing. Many researchers had proposed multiple design schemes of unipolar orthogonal codes and their sets. One of these code-sets was proposed by Robinson in 1967 in his research paper [7]. At the same time in 1967 Gold, R. proposed optimal binary sequences for spread spectrum multiplexing [8]. In 1971, Reed proposed a new scheme to generate kth order near-orthogonal codes [9], while in 1979 Shedd and Sarwate proposed another scheme for design of binary orthogonal sequences [10]. The orthogonal binary sequences design was in its early stage and there was a need to convert these binary codes into optical signal.

In 1994, Kwong, Zhang and Yang proposed 2n prime sequence codes and its optical CDMA coding architecture [13].

In 1995, Argon and Ahmad [14] proposed optimal optical orthogonal code design using difference sets and projective geometry.

Choudhary, Chatterjee, and John had proposed new code sequences for fiber optic CDMA systems [15]. These new code sequences were based on table of prime, quadratic residues and number theory. Bitan and Etzion had proposed constructions of optimal constant weight cyclically permutable codes based on difference families [16].

In 1996, Zhang had proposed strict optical orthogonal codes for purely asynchronous code division multiple access applications [17].

In 2001, Choudhary, Chatterjee, & John proposed one dimensional optical orthogonal codes using hadamard matices [18].

In 2011, R.C.S. Chauhan and R. Asthana propsed an unique representation named be difference of positions representation (DoPR) and simple calculation of auto-correlation and cross-correlation constraint of one dimensional unipolar orthogonal codes based on DoPR [21].

In 1995, G. C. Yang and T. E. Fuja proposed one dimensional optical orthogonal codes with unequal auto- and cross-correlation constraints [19]. In 1996, G. C. Yang, also proposed variable weight optical orthogonal codes for CDMA networks with multiple performance requirements [20].

Some of the researchers are doing experimental demonstration of the optical cdma systems. In 1991, Macdonald and Vethanayagam demonstrated a novel optical code division multiple access system at 800 mega-chips per second [22]. In 1994, Gagliardi and Mendez gave synthesis of high speed and bandwidth efficient optical code division multiple access and its demonstration at 1Gb/s throughput [23]. In 2002, Sotobayashi, Chujo and Kityama had demonstrated 1.6-b/s/Hz, 6.4-Tb/s QPSK-OCDM/WDM (4 OCDM X 40 WDM X 40 Gb/s) transmission using optical hard thresholding [23].

III. ILLUSTRATION OF ONE DIMENSIONAL UNIPOLAR ORTHOGONAL CODES

A. *Weighted Positions Representation (WPR)*

The one dimensional unipolar orthogonal code word X of code length n and code weight w includes w number of bit 1's and n-w number of bit 0's. There are n positions of either bit 1 or bit 0 in code X which are termed as 0th position to $(n-1)^{th}$ position out of which there are w weighted positions and n-w non weighted positions. The code X can be represented by showing weighted positions of code X. There can be such n representations for each of n circular shifted versions of code X. This type of representation of an unipolar orthogonal codeword may be called as weighted positions representation (WPR) or bit 1's positions representation. For example suppose an one dimensional unipolar orthogonal code X of code length n=19, code weight w=4 such that X= 1000100001000000100, which can be represented as WPR (0,4,9,16). Each of n circular shifted versions of code X represent to same unipolar orthogonal code X. All other weighted positions representations of code X can be given as (3,8,15,18), (2,7,14,17), (1,6,13,16), (0,5,12,15), (4,11,14,18), (3,10,13,17), (2,9,12,16), (1,8,11,15), (0,7,10,14), (6,9,13,18), (5,8,12,17), (4,7,11,16), (3,6,10,15), (2,5,9,14), (1,4,8,13), (0,3,7,12), (2,6,11,18), (1,5,10,17). Anyone of these can be used to represent the one dimensional unipolar orthogonal code X supposed as above in WPR [24].

B. *Fixed Weighted Position Representation (FWPR)*

The n representations of an unipolar code in WPR can be reduced by making a compulsory position of bit 1 at position zero. This will reduce the number of weighted positions representations of the unipolar orthogonal code to w from n representations. This reduced weighted positions representation may be called as fixed weighted positions representation (FWPR). The code X in FWPR can be given as $X_{F0} = X_0(f_0, f_1, \dots\dots, f_{(w-1)})$ which means that the positions $X_0(f_0), X_0(f_1), \dots\dots\dots X_0(f_{(w-1)})$ are '1' (weighted) while other 'n-w' positions are '0' (nonweighted). The shifting of X in binary form by $X_0(f_1), X_0(f_2), \dots\dots\dots X_0(f_{(w-1)})$, units in left circularly convert the code X into other FWPRs like $X_{F1}, X_{F2}, \dots, X_{F(w-1)}$

$$X_{F1} = X_1(f_0, f_1, \dots\dots, f_{(w-1)})$$
$$X_{F2} = X_2(f_0, f_1, \dots\dots, f_{(w-1)})$$
$$\dots\dots\dots$$
$$X_{F(w-1)} = X_{w-1}(f_0, f_1, \dots\dots, f_{(w-1)})$$

$$X_F = \begin{bmatrix} X_{F0} \\ X_{F1} \\ \vdots \\ \vdots \\ X_{F(w-1)} \end{bmatrix} = \begin{bmatrix} X_0(f_0) & X_0(f_1) & \dots & X_0(f_{w-1}) \\ X_1(f_0) & X_1(f_1) & \dots & X_1(f_{w-1}) \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ X_{w-1}(f_0) & X_{w-1}(f_1) & \dots & X_{w-1}(f_{w-1}) \end{bmatrix}$$

The code X in its matrix FWPR X_F contains all FWPR $X_{F0}, X_{F1}, X_{F2}, \dots, X_{F(w-1)}$ of code X in the rows of matrix FWPR, F X. These rows of F X always have atleast one common element weighted at zero position so that the first column of code F X is always zero. For the same example as for WPR, X=1000100001000000100, the fixed weighted position representations of code are given as WPR with 0th weighted positions like (0,4,9,16), (0,5,12,15), (0,7,10,14), and (0,3,7,12).

The matrix FWPR for this code X is given as

$$X_F = \begin{bmatrix} 0 & 4 & 9 & 16 \\ 0 & 5 & 12 & 15 \\ 0 & 7 & 10 & 14 \\ 0 & 3 & 7 & 12 \end{bmatrix}$$

Such FWPR representation of an unipolar orthogonal code is not unique as it has w representations of an orthogonal code. To make the representation of an orthogonal code as unique, a new representation is proposed which shows the difference of positions of consecutive bit 1's in the unipolar code or binary sequence [25].

C. *Difference of Position Representation (DoPR)*

An orthogonal codeword represented in WPR or FWPR has w elements in its representations. These representations do not uniquely represent an one dimensional unipolar orthogonal code. If this code is represented by difference of positions of consecutive bit 1's in the code or difference of consecutive weighted positions in WPR or FWPR, all n circular shifted versions of the unipolar code can be represented uniquely. In this difference of positions representation (DoPR) the first DoP element is equal to difference of first two element of any WPR or FWPR of the unipolar code, the second DoP element is equal to difference of third and second element of same WPR or FWPR and so on upto (w-1)th DoP element which is equal to difference of last two elements of same WPR or FWPR. The last DoP element is given by difference of first and last element of WPR or FWPR of the code in modulo n addition/subtraction, here n is length and w is weight of 1-D UOC. For a given unipolar code X in FWPR, $X_{F0} = X_0(f_0, f_1, \dots\dots, f_{(w-1)})$ of code length n and weight w, it can be represented as $X_{D0} = X_0(d_0, d_1, \dots\dots, d_{(w-1)})$ in DoPR. Here

$$X_0(d_0) = X_0(f_1) - X_0(f_0)$$
$$X_0(d_1) = X_0(f_2) - X_0(f_1)$$
$$\dots\dots$$
$$X_0(d_{w-2}) = X_0(f_{w-1}) - X_0(f_{w-2})$$
$$X_0(d_{w-1}) = (X_0(f_0) - X_0(f_{w-1}))mod(n)$$

In this difference of positions representation, all w circular shifted versions of DoPR, represent to same unipolar code. From these all circular shifted versions of DoPR, one DoPR of the code can be standardized by fixing last DoP as the greatest element. If last DoP element is the greatest but equal to other DoP elements in the DoPR, then more than one DoPRs are found with greatest last DoP element. Out of these selected DoPRs, one DoPR can be standardized by searching an DoPR with minimum value of first DoP element. If suppose more than one DoPRs are found with the maximum last DoP element and minimum first DoP element then out of these selected DoPRs one DoPR can be standardized by searching an DoPR with minimum second DoP element. If suppose DoPR could not be standardized, it can be proceeded upto minimum (w-1)th DoP element to get a standard DoPR of the same unipolar code. The sum of all DoP elements of a DOPR for the unipolar code is always equal to code length n. The code X in DoPR $X_{D0} = X_0(d_0, d_1, \dots\dots, d_{(w-1)})$ can be converted in FWPR

$$X_0(f_0) = X_1(f_0) = \cdots = X_{(w-1)}(f_0) = 0;$$
$$X_0(f_1) = X_1(d_0)$$

As

$$X_0(f_2) = X_0(d_0) + X_0(d_1),$$
$$\dots\dots$$
$$X_0(f_{w-1}) = X_0(d_0) + X_0(d_1) + \cdots + X_0(d_{w-2})$$

The matrix FWPR of code $X_{D0} = X_0(d_0, d_1, \dots\dots, d_{(w-1)})$ can be given as following:

$$X_F = \begin{bmatrix} X_{F0} \\ X_{F1} \\ \vdots \\ \vdots \\ X_{F(w-1)} \end{bmatrix} = \begin{bmatrix} 0 & X_0(d_0) & \dots & X_0(d_0) + X_0(d_1) \dots + X_0(d_{w-2}) \\ 0 & X_0(d_1) & \dots & X_0(d_1) + X_0(d_2) \dots + X_0(d_{w-1}) \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ 0 & X_0(d_{w-1}) & \dots & X_0(d_{w-1}) + X_0(d_0) \dots + X_0(d_{w-2}) \end{bmatrix}$$

The matrix elements are calculated using modulo n addition. All of these can be best understood by the example supposed earlier, the unipolar code X = FWPR (0, 4, 9, 16) with code length n=19 and weight w=4. The DoPR of this code can be determined for all other FWPRs of same code as following:

FWPR(0,4,9,16)=DoPR(4-0, 9-4, 16-9, 0-16+19)=DOPR(4,5,7,3)
FWPR(0,5,12,15)=DoPR(5,7,3,4)
FWPR(0,7,10,14)=DoPR(7,5,4,5)
FWPR(0,3,7,12)=DoPR(3,4,5,7)

All w=4 circular shifted version of this DoPR (4,5,7,3), are given as DoPR (5,7,3,4), DoPR(7,3,4,5) and DoPR(3,4,5,7) which represent to same unipolar ortohognal code. One of this DoPR can be standardized by keeping last DoP element as the greatest as found in DoPR (3,4,5,7). The matrix FWPR for standard DoPR (3,4,5,7) can be given as:

$$X_F = \begin{bmatrix} 0 & 3 & 7 & 12 \\ 0 & 4 & 9 & 16 \\ 0 & 5 & 12 & 15 \\ 0 & 7 & 10 & 14 \end{bmatrix}$$

There is another DoPR can be proposed named extended difference of positions representation (EDoPR), containing all difference of positions of bit '1's which are at consecutive or non-consecutive positions. These positions can be arranged in matrix w×(w−1) form.

In general for any value of weight w such that w< n , the code X in DoPR $X_{D0} = X_0(d_0, d_1, \ldots\ldots, d_{(w-1)})$ can be converted in EDoPR as follows:

$$X_{D_0} = EDOPR \begin{bmatrix} X_0(d_0) & X_0(d_0)+X_0(d_1) & \cdots & X_0(d_0)+X_0(d_1)\cdots+X_0(d_{w-2}) \\ X_0(d_1) & X_0(d_1)+X_0(d_2) & \cdots & X_0(d_1)+X_0(d_2)\cdots+X_0(d_{w-1}) \\ \vdots & & \vdots & \vdots \\ X_0(d_{(w-1)}) & X_0(d_{(w-1)})+X_0(d_0) & \cdots & X_0(d_{(w-1)})+X_0(d_0)+\cdots+X_0(d_{(w-2)}) \end{bmatrix}$$

For DOPR (3, 4, 5, 7), the EDOPR can be given as

$$DOP(3,4,5,7) = EDOP \begin{bmatrix} 3 & 7 & 12 \\ 4 & 9 & 16 \\ 5 & 12 & 15 \\ 7 & 10 & 14 \end{bmatrix}$$

It can be concluded from above matrix FWPR and EDOPR, for code X= $X_{D0} = X_0(d_0, d_1, \ldots\ldots, d_{(w-1)})$, that both are almost same except the extra first column in FWPR with all zero elements. Hence both are easily convertible.

Either of these two makes calculation of auto and cross correlation constraints of unipolar orthogonal codes very easier [26].

IV. CALCULATION OF CORRELATION CONSTRAINTS

In following the conventional method for calculation of auto-correlation and cross-correlation constraints is described. As well as one proposed method for calculation of correlation constraint using fixed weighted position representation (FWPR) and another using extended difference of positions representation (EDoPR) are described. These proposed methods are found with reduced computational complexity.

A. *Conventional Method*

A unipolar orthogonal code is represented by n binary sequences for every circular shifting of the code in WPRs. The correlation of a uni-polar orthogonal code with its un-shifted binary sequence is equal to weight 'w' of the code. Suppose code X with code length 'n' and weight 'w' be suppose code X with code length 'n' and weight 'w' be X = (x0 x1 x2 . . . xn-1), xt = 0 or 1 for 0 <=*t* <=*n-1*

The correlation of X with its un-shifted sequence is given by

$$R_{XX} = \sum_{t=0}^{n-1} X_t X_t$$

which, will be always equal to w. It is also autocorrelation peak which appear at the detector for the detection of binary data equal to '1' represented by this codeword.

The code X with m unit cyclic left shifting is represented as Xm = (xm xm+1 xm+2 . . . xm-1), xm+t is given under modulo n addition for 0 <=*t* <=*n-1*,

The correlation of X with Xm (the cyclically shifted versions) is given by

$$R_{XX} = \sum_{t=0}^{n-1} X_t X_{t\oplus m} \qquad 0 < m \le n-1$$

The auto-correlation constraint λ_a is defined and given as

$$\lambda_a = \text{Maximum of } R_{XX_1}, R_{XX_2}, \ldots, R_{XX_{n-1}} \qquad \text{or}$$

$$\lambda_a = \sum_{t=0}^{n-1} X_t X_{t\oplus m} \qquad 0 < m \le n-1$$

For unipolar orthogonal binary sequences, $0 \le \lambda_a \le$ w - 1

Suppose code Y with code length 'n' and weight 'w' be Y = $(y_0\ y_1\ y_2\ \ .\ .\ .\ y_{n-1})$.

y_t = 0 or 1 for 0 ≤ t ≤ n-1

The correlation of X with Y and its circularly unshifted & shifted binary sequences (Ym) is given as

$R_{XY_m} = \sum_{t=0}^{n-1} x_t y_{t\oplus m}$ $0 \le m \le n-1$

The cross-correlation constraint λ_c is defined and given as λ_c= Maximum of $(R_{XX_1}, R_{XX_2}, \ldots, R_{XX_{n-1}})$ or

$$\lambda_c \ge \sum_{t=0}^{n-1} x_t y_{t\oplus m} \qquad 0 \le m \le n-1$$

For uni-polar orthogonal binary sequences

$0 \le \lambda_c \le$ w – 1 [25]

B. *A Method for Calculation of Correlation Constraints Using FWPR*

In the calculation of auto-correlation constraint of code X, the maximum common weighted positions are observed in all FWPRs of code X or in two rows of matrix FWPR X_F. The code X in its matrix FWPR X_F contains all FWPR $X_{F0}, X_{F1}, X_{F2}, \ldots, X_{F(w-1)}$ of code X in the rows of matrix FWPR X_F.

$$X_F = \begin{bmatrix} X_{F0} \\ X_{F1} \\ \vdots \\ X_{F(w-1)} \end{bmatrix} = \begin{bmatrix} X_0(f_0) & X_0(f_1) & \cdots & X_0(f_{w-1}) \\ X_1(f_0) & X_1(f_1) & \cdots & X_1(f_{w-1}) \\ \vdots & \vdots & \vdots & \vdots \\ X_{w-1}(f_0) & X_{w-1}(f_1) & \cdots & X_{w-1}(f_{w-1}) \end{bmatrix}$$

These rows of X_F always have at least one common element weighted at zero position so that the first column of code X_F is always zero. The auto-correlation constraint of code X can be calculated by comparing each row with all other rows of code X in matrix FWPR. The first row is compared with all other rows of X_F , second row is compared with third and so on upto (w-1)th row, fourth row is compared with fifth and so on upto (w-1)th row, similarly upto (w-2)th row which is compared with (w-1)th row to get maximum common weighted positions. This maximum common position in two rows is called as auto-correlation constraint λ_a. It can be given as follows:

$$R_{X_{Fi}X_{Fj}} = \max_{s=0} \sum_{t=0}^{w-1} X_i(f_s)X_j(f_t), \qquad for\ i \ne j.$$

$$\text{Here } X_i(f_s)X_j(f_t) = \begin{cases} 1, & for \quad X_i(f_s) = X_j(f_t) \\ 0, & otherwise \end{cases}$$

for $0 \le i < w-1$, $i+1 \le j \le w-1$, $0 \le s, t \le w-1$

The auto-correlation constraint of code X, can be calculated as

$$\lambda_a = Max\left(R_{X_{Fi}X_{Fj}}\right), for\ 0 \le i < w-1, i+1 \le j \le w-1, or$$

$$\lambda_a = \max_{i=0}^{w-2} \max_{j=i+1}^{w-1} \left(R_{X_{Fi}Y_{Fj}}\right) \quad or$$

$$\lambda_a = \max_{i=0}^{w-2} \max_{j=i+1}^{w-1} \max_{s=0}^{w-1} \sum_{t=0}^{w-1} X_i(f_s)X_j(f_t), \ or$$

$$\lambda_a \ge \sum_{t=0}^{w-1} X_i(f_s)Y_j(f_t), \ for\ 0 \le s \le w-1, 0 \le i < w-1, i+1 \le j \le w-1$$

The computational complexity for the calculation of auto-correlation constraint of unipolar orthogonal code is of the order O(W^4) .

Similarly for two codes X and Y of same code length ‘n’ and weight ‘w’, the cross-correlation constraint λ_a can be calculated in FWPR,

$X_{F0} = X_0(f_0, f_1, \dots, f_{w-1})$ $Y_{F0} = Y_0(f_0, f_1, \dots, f_{w-1})$

$$Y_F = \begin{bmatrix} Y_{F0} \\ Y_{F1} \\ \vdots \\ Y_{F(w-1)} \end{bmatrix} = \begin{bmatrix} y_0(f_0) & Y_0(f_1) & \dots & Y_0(f_{w-1}) \\ Y_1(f_0) & y_1(f_1) & \dots & Y_1(f_{w-1}) \\ \vdots & \vdots & \vdots & \vdots \\ Y_{w-1}(f_0) & Y_{w-1}(f_1) & \dots & Y_{w-1}(f_{w-1}) \end{bmatrix}$$

The cross-correlation of X with Y can be calculated by comparing each row of XF with all rows of X_F represented in matrix fixed weighted position representation (FWPR).

Every row of an unipolar orthogonal code in matrix FWPR represent to same code in weighted position representation with at least one position weighted at zero position. Here all such row of code X are compared with all rows of code Y to get maximum common weighted positions in code X and Y, this maximum common position is cross-correlation constraint for pair of code X and code Y. The correlation function between i[th] row of code X_F and j[th] row of code Y_F can be given as follows:

$$R_{X_{Fi}Y_{Fj}} = \max_{s=0} \sum_{t=0}^{w-1} X_i(f_s)Y_j(f_t), \qquad for\ \ 0 \le i,j \le w-1.$$

Here $X_i(f_s)Y_j(f_t) = \begin{cases} 1, & for \quad X_i(f_s) = Y_j(f_t) \\ 0, & otherwise \end{cases}$

For, ∀(i, j, s,t) . The cross-correlation constraint λ_c of code X and Y, can be calculated as-

$$\lambda_c = Max\left(R_{X_{Fi}Y_{Fj}}\right) + 1, for\ 0 \le i,j \le w-1, or$$

$$\lambda_c = \max_{i=0}^{w-1} \max_{j=0}^{w-1} \left(R_{X_{Fi}Y_{Fj}}\right) + 1 \quad or$$

$$\lambda_c = \max_{i=0}^{w-1} \max_{j=0}^{w-1} \max_{s=0}^{w-2} \sum_{t=0}^{w-2} X_i(f_s)Y_i(f_t) + 1, \ or$$

$$\lambda_c \ge \sum_{t=0}^{w-2} X_i(f_s)Y_i(f_t) + 1, \ for\ 0 \le i,j \le w-1, 0 \le s < w-1$$

The computational complexity for the calculation of cross-correlation constraint for a pair of one dimensional unipolar orthogonal codes is of the order O(W^4).

C. A Method for calculation of correlation constraint using EDOPR

The code X in standard DoPR is $X_{D0} = X_0(d_0, d_1, \dots, d_{w-1})$ with code length $n = X_0(d_0) + X_0(d_1) + \dots + X_0(d_{w-1})$

Its equivalent in EDoPR, is given as

$$X_E = \begin{bmatrix} X_{E0} \\ X_{E1} \\ \vdots \\ X_{E(w-1)} \end{bmatrix} = EDoPR \begin{bmatrix} X_0(e_0) & X_0(e_1) & \dots & X_0(e_{w-2}) \\ X_1(e_0) & X_1(e_1) & \dots & X_1(e_{w-2}) \\ \vdots & \vdots & \vdots & \vdots \\ X_{w-1}(e_0) & X_{w-1}(e_1) & \dots & X_{w-1}(e_{w-2}) \end{bmatrix}$$

$$X_{D_0} = EDOPR \begin{bmatrix} X_0(d_0) & X_0(d_0) + X_0(d_1) & \dots & X_0(d_0) + X_0(d_1) \dots + X_0(d_{w-2}) \\ X_0(d_1) & X_0(d_1) + X_0(d_2) & \dots & X_0(d_1) + X_0(d_2) \dots + X_0(d_{w-1}) \\ \vdots & & \vdots & \vdots \\ X_0(d_{(w-1)}) & X_0(d_{(w-1)}) + X_0(d_0) & \dots & X_0(d_{(w-1)}) + X_0(d_0) + \dots + X_0(d_{(w-2)}) \end{bmatrix}$$

The auto-correlation constraint of code X can be calculated by comparing each row with all other rows of code X in extended difference of positions representation (EDoPR). The first row is compared with all other rows of X , second row is compared with third and so on upto (w-1)[th] row, fourth row is compared with fifth and so on upto (w-1)[th] row, similarly upto (w-2)[th] row which is compared with (w-1)[th] row to get maximum common weighted positions. This maximum common positions plus one is termed as auto-correlation constraint λ_a because the first column with all zero elements in matrix FWPR of code X is not present in EDoPR of code X. The first column in matrix FWPR with all zero elements is always understood in EDOPR to justify for at least one more common element in comparison of each pair of rows of EDoPR of code X. It can be given as follows. The correlation function between i[th] and j[th] row of code X_E can be given as follows

$$P_{X_{Ei}Y_{Ej}} = \max_{s=0}^{w-2} \sum_{t=0}^{w-2} X_i(e_s)X(e_t), \qquad for\ i \ne j.$$

Here $X_i(e_s)X_j(e_t) = \begin{cases} 1, & for \quad X_i(e_s) = X_j(e_t) \\ 0, & otherwise \end{cases}$

, for $0 \le i < w-1$, $i+1 \le j \le w-1$, $0 \le s,t \le w-2$

The auto-correlation constraint λ_a of code X, can be calculated as

$$\lambda_a = 1 + Max\left(P_{X_{Fi}X_{Fj}}\right), for\ 0 \le i < w-1, i+1 \le j \le w-1, or$$

$$\lambda_a = 1 + \max_{i=0}^{w-2} \max_{j=i+1}^{w-1} \left(P_{X_{Fi}X_{Fj}}\right) \quad or$$

$$\lambda_a = 1 + \max_{i=0}^{w-2} \max_{j=i+1}^{w-1} \max_{s=0}^{w-1} \sum_{t=0}^{w-2} X_i(f_s)X_j(f_t), \ or$$

$$\lambda_a \ge 1 + \sum_{t=0}^{w-1} X_i(f_s)X_j(f_t), \ for\ 0 \le s \le w-2, 0 \le i < w-1, i+1 \le j \le w-1$$

The computational complexity for the calculation of auto-correlation constraint of unipolar orthogonal code is of the order O(W^4).

Similarly for two codes X and Y of same code length ‘n’ and weight ‘w’, the cross-correlation constraint λ_c can be calculated in EDoP.

$X_{D0} = X_0(d_0, d_1, \dots, d_{w-1})$ $Y_{D0} = Y_0(d_0, d_1, \dots, d_{w-1})$

$$X_{DO} = Y_F = \begin{bmatrix} Y_{E0} \\ Y_{E1} \\ \vdots \\ \vdots \\ Y_{E(w-1)} \end{bmatrix} = \begin{bmatrix} y_0(e_0) & Y_0(e_1) & \cdots & Y_0(e_{w-2}) \\ Y_1(e_0) & y_1(e_1) & \cdots & Y_1(e_{w-2}) \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ Y_{w-1}(e_0) & Y_{w-1}(e_1) & \cdots & Y_{w-1}(e_{w-2}) \end{bmatrix}$$

The cross-correlation of X with Y can be calculated by comparing each row of X_E with all rows of Y_E represented in extended difference of positions representation (EDoPR). Every row of an unipolar orthogonal code in matrix EDoPR represent to same code in fixed weighted position representation without the weighted zero position. Here all such row of code X are compared with all the rows of code Y in EDoPR, to get maximum common elements. This maximum common elements plus one is equivalent to cross-correlation constraint for pair of code X and code Y because the first column with all zero elements in matrix FWPR of code X and code Y is not present in EDoPR of code X and Y.

The first column in matrix FWPR with all zero elements is always understood in EDOPR to justify for at least one more common element in comparison of each pair of rows of EDoPR of code X .The correlation function between i[th] row of code X_E and j[th] row of code Y_E can be given as follows:

$$P_{X_{Fi}Y_{Fj}} = \max_{s=0}^{w-2} \sum_{t=0}^{w-2} X_i(f_s)Y_j(f_t), for \ \ 0 \le i,j \le w-1.$$

Here

$$X_i(f_s)Y_j(f_t) = \begin{cases} 1, & for \quad X_i(f_s) = Y_j(f_t) \ for \ \forall (i,j,s,t) \\ 0, & otherwise \end{cases}$$

The cross-correlation constraint λ_c of code X and Y, can be calculated as

$$\lambda_c = Max\left(P_{X_{Ei}Y_{Ej}}\right) + 1, for \ 0 \le i,j \le w-1, or$$

$$\lambda_c = \max_{i=0}^{w-1} \max_{j=0}^{w-1} \left(P_{X_{Ei}Y_{Ej}}\right) + 1 \quad or$$

$$\lambda_c = \max_{i=0}^{w-1} \max_{j=0}^{w-1} \max_{s=0}^{w-2} \sum_{t=0}^{w-2} X_i(e_s)Y_i(e_t) + 1, \ \ or$$

$$\lambda_c \ge \sum_{t=0}^{w-2} X_i(e_s)Y_i(e_t) + 1, \ \ for \ 0 \le i,j \le w-1, 0 \le s < w-1$$

The computational complexity for the calculation of cross-correlation constraint for a pair of one dimensional unipolar orthogonal code is of the order. The calculation of auto- correlation and cross correlation constraint for the set of one dimensional unipolar orthogonal code can be explained as following.

Suppose the set of unipolar orthogonal codes contains two or more than two codes. The auto correlation constraint of every code of the set can be calculated by following conventional or proposed methods for the calculation of correlation constraints. The maximum of these calculated auto-correlation constraints of all the codes is called auto-correlation constraint for the set of codes. Similarly the cross-correlation constraint for every pair of codes from same set can be calculated by conventional or proposed methods for the calculation of correlation constraints. The maximum of these calculated cross-correlation constraints of all pair of codes from the same set is called cross-correlation constraint for the set of unipolar orthogonal codes O(W^4).

V. MAXIMAL CLIQUE SETS OF 1-DUOC

The maximal sets of 1-DUOC for fixed code parameters (n,w, λ_a,λ_c) can be designed using anyone of the two proposed algorithms.

A. *Algorithm One to design the maximum sets of 1-DUOC:*

The algorithm one can generate all possible multiple sets of one dimensional unipolar orthogonal codes for given code length *'n'*, code weight *'w'* and correlation constraints lying from 1 to w-1, such that *w* and *n* are co-prime (no common factors) and W^2 <*n* . The codes are generated in difference of positions representation (DoPR). The steps of algorithm one as follows:

Step-1: Input code length *'n'*, code weight *'w'*, auto-correlation constraint λ_a and cross-correlation constraint λ_c for the code sets to be generated.

Step-2: Initialize *w* variables $a_1, a_2, \dots, a_{w-1}$equal to one and $a_{w=(n-(a_1,a_2,\dots,a_{w-1}))}$.

Step-3: Generate all the codes of set (*n*,*w*) in standardized DoPR in sequence starting from (1,1,...,1,*n* –*w*+1) to $a_1, a_2, \dots, a_w$ with enumeration.

$$a_w \ge (a_1, a_2, \dots, a_{w-1}) \ge 1$$

$$\left\lceil \frac{n}{w} \right\rceil \le a_w \le (n-w+1)$$

The variables $(a_1, a_2, \dots, a_{w-1}, a_w)$ in DoPR, represent the difference of weighted positions or position of bit 1's in serial and circular order in the code.

All the codes generated with condition $a_w > (a_1, a_2, \dots, a_{w-1})$ will always be in standard DoP representation. While for the condition when a_w is equal to any one or more than one of $(a_1, a_2, \dots, a_{w-1}, a_w)$ and greater than remaining DoP elements, the code has more than one representations as $(a_1, a_2, \dots, a_{w-1})$ out of their circular shifted versions. In this condition, that representation is chosen for which (i) a_1 is minimum, and (ii) If minimum a_1 is found in more than one DoP representations, then minimum a_2 is searched among DoPs with minimum a_1 . The DoP representation with minimum a_1 and minimum a_2 is considered as standard DoP representation. Similarly, search up to a_{w-1} to find standard DoP representation may be needed if $(a_1, a_2, \dots, a_{w-2})$ are same in more than two members of candidate codes. The upper bound of the set (*n*,*w*) of these generated unipolar orthogonal codes is equal to Johnson bound for the set of unipolar orthogonal codes with maximum correlation constraints $\lambda_a = \lambda_c = w-1$ These generated unipolar codes in DoPR are numbered serially from Code#1 to Code #N for identification of codes. *N* is maximum number of codes generated.

$$N = \left\lfloor \frac{(n-1)(n-2)\dots(n-w+1)}{w(w-1)\dots 2.1} \right\rfloor$$

Here $\lfloor a \rfloor$ represent integer value just less than a, and $\lceil a \rceil$ represent integer value just greater than a.

Step 4: Calculation of auto-correlation constraints

For the generated codes in DoPR in step 3, the auto-correlation constraint of each code can be calculated through the use of proposed method for calculation of correlation constraints.

Step 5: Calculation of cross-correlation constraints

The cross-correlation constraint for each pair of unipolar orthogonal codes generated in step-3, is calculated through the use of proposed method. The cross-correlation for each pair containing code#1 with code of code number greater than 1, secondly the code#2 with code of code number greater than 2, up to code#(N-1) with code#N.

Step 6: Formation of correlation matrix

In step 3, the number of generated codes are N. A $N*N$ matrix can be formed in such a way that

it contains correlation of code# x with code# y, for $1\leq (x, y) \leq N$.

When $x = y$, it represent maximum auto-correlation for non zero shift or auto-correlation constraint of code# x or code# y, which form diagonal elements of $N*N$ correlation matrix. For $x\neq y$, cross correlation constraint of code# x with code# y is found as a non-diagonal element in row x and column y as well as non-diagonal position with row y and column x in correlation matrix.

Step 7: Formation of sets of unipolar orthogonal codes for given values of λ_a and λ_c such that $1\leq \lambda_a, \lambda_c \leq w-1$. The upper bound Z of the set of unipolar orthogonal codes with given values of auto-correlation and cross-correlation constraints can be calculated by Johnson bound A.

$$Z = \left\lfloor \frac{(n-1)(n-2)\dots(n-\lambda)}{w(w-1)\dots(w-\lambda)} \right\rfloor, here\ \lambda = \max(\lambda_a, \lambda_c)$$

Now, all those codes are selected for which diagonal entries are $\leq \lambda_a$. All the elements of rows and columns, which are not selected, are removed from the correlation matrix, giving a reduced correlation matrix. Within these codes, only those sets of codes with upper bound Z, are selected which has cross-correlation constraints $\leq \lambda_c$ by following method.

i. From the reduced correlation matrix only those rows and columns are selected whose numbers of cross-correlation entries with $\leq \lambda_c$ are greater than the upper bound Z of the sets of codes to be generated.

ii. In this reduced correlation matrix, number of rows or columns are equal to M. Out of these M codes, all possible combinations of sets of non repeated Z codes are formed mentioning their code numbers. These possible combinations of sets are equal to

$$G = M_{c_z} = \frac{M(M-1)..(M-Z+1)}{Z(Z-1)\dots 2.1}$$

iii. Each such set of codes are checked for their maximum cross-correlation constraint $\leq \lambda_c$ through the use of cross-correlation entries from reduced correlation matrix. It will achieve final sets of codes as required.

VI. COMPUTATIONAL COMPLEXITY

The computational complexity of the proposed algorithm - one for the formation of one dimensional unipolar (optical) orthogonal codes is summarized here in the following steps:

Step 1: Calculation for upper bound of the set of one dimensional unipolar (optical) orthogonal codes for code length n, code weight w with auto-correlation and cross-correlation constraint of the set equal to w-1. This upper bound is equal to Johnson bound A. The computational complexity of this step is $O(nw)$.

Step 2: Formation of all one dimensional unipolar (optical) orthogonal codes of code length n, code weight w with auto-correlation and cross-correlation constraint less than or equal to w-1 in standard difference of positions representation (DoPR). The computational complexity of this step is $O(n^{w-1})$

Step 3: Conversion of every code formed in standard DoPR to extended DoP matrix representation. The computational complexity of this step is $O(rw^2)$.

Step 4: Calculation of auto-correlation constraint of each code formed at step 2 form its EDOP matrix representation as in step 3. These values of auto-correlation constraints are put at the position of diagonal elements in correlation matrix $[r*r]$. The computational complexity of this step is $O(rw^3)$.

Step 5: Calculation of cross-correlation constraint of every pair of these codes in EDoP matrix representation and putting them in correlation matrix $[r*r]$ at non diagonal positions. The computational complexity of this step $O(r^2w^3)$.

Step 6: Calculation for upper bound or Johnson bound of the set of one dimensional unipolar (optical) orthogonal codes for code length n, code weight w with correlation constraint λ which is maximum of given auto-correlation and cross-correlation constraint. The computational complexity of this step is $O(n\lambda)$.

Step 7: Formation of reduced correlation matrix whose diagonal elements are always less than or equal to given auto-correlation constraint λ_a and non-diagonal elements are either less than or greater than or equal to cross-correlation constraint λ_c. The computational complexity of this step is $O(r^2)$.

Step 8: Formation of all sets of 1-D U(O)OC with maximum cardinality as calculated in step VI, and checking each set for cross-correlation constraint less than or equal to given cross-correlation constraint value with help of reduced correlation matrix. The computational complexity of this step is $O(r^3)$, where

$$r = \frac{(n-1)(n-2)\dots(n-w+1)}{w(w-1)(w-2)..2.1} \approx (^n/_w)^w$$

The overall computational complexity of the proposed algorithm is of the higher order of $O(r^3)$ which is equivalent $O((^n/_w)^{3w})$ which may be polynomial type for w<<n.

A. *Design of Sets of 1-DUOC (Algorithm - two)*

The algorithm two is an extended version of algorithm one. In algorithm one the formation of correlation matrix (NxN) is much complex for higher N so that N cannot take the values greater than 100. The formation of code sets from the given correlation matrix (NxN) is also much complex. It can be reduced by following algorithm two as given below:

Step 1: same as algorithm one (input code parameters $(n, w, \lambda_a, \lambda_c)$)

Step 2: same as algorithm one (initializing parameters)

Step 3: same as algorithm one (generation of all the N codes in sequence in DoPR)

Step 4: same as algorithm one (calculation of auto-correlation constraint of each of N codes generated at step 3)

Step 5: Take one code C_1 out of all N codes such that maximum non-zero shift auto-correlation of code C_1 is less than or equal to auto-correlation constraint λ_a of desired sets as input in step one. Calculate cross-correlation of pair of codes formed with other N-1 codes such that in each pair one code is C_1. Out of N-1 pair of codes only N1 codes pairing with C_1 are selected which have cross correlation less than or equal to cross correlation constraint λ_c.

Step 6: Repeat step 5 for code C_2 out of all N_1 codes. Get N_2 codes pairing with C_2 out of $(N_1$-1) pair of codes. The step 6 is repeated till the C_z-1. Where Z is defined and given as maximum number of codes in the code set formed for given code parameters (n,w,λ_a,λ_c) such that $(C_1, C_2, \dots, C_{z-1})$ have cross-correlation constraint less than or equal to λ_c. There are total N_z-1 code which have their cross-correlation value with code C_z-1 less than or equal to λ_c. Each of these N_z-1 codes may be treated as code C_z so that there are Nz-1 set of codes may be formed as $(C_1, C_2, \dots, C_{z-1}, Cz)$

Step 7: The step 6 may be repeated for all possible other codes C_1 to C_{z-1} which are not employed in last steps to get different set of codes following correlation properties.

COMPUTATIONAL COMPLEXITY

The computational complexity of step 1 to step 7 is remain same as algorithm - one but the value of r is changed for given auto-correlation λ_a and cross-correlation constraint λ_c.

$\lambda = \max(\lambda_a, \lambda_c)$

$$r = \frac{(n-1)(n-2)\dots(n-\lambda)}{w(w-1)(w-2)\dots(w-\lambda)} \approx (n/w)^w$$

The overall computational complexity of the proposed algorithm - two is of the higher order of $O(r^3)$ which is equivalent $O((n/w)^{3w})$ which may be polynomial type for $w \ll n$ but less complex than algorithm - one.

VII. CONCLUSION

The proposed difference of positions representation of one dimensional unipolar orthogonal codes can be used as unique representation for these codes. The fixed weighted position representation is not unique but matrix FWPR of an unipolar orthogonal code can be used for calculation of correlation constraints with computational complexity with order of $O(w^4)$. Another method for calculation of correlation constraints using EDoPR for unipolar orthogonal codes is found with near about same computational complexity with the order (w^4) .

In this paper the proposed clique search algorithm design the family of sets of codes with multi-length, multi-weight, auto-correlation constraint equal to one and cross-correlation constraint equal to one for within set while cross-correlation constraint equal to two among the sets with upper bound. The computational complexity of the proposed algorithm designing the multiple sets of codes with variable and general code parameters is polynomial type if clique search is polynomial.

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