A Survey to Optical CDMA Systems – Part I: Optical Orthogonal Encoding

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***Abstract*— Optical CDMA (Code Division Multiple Access) is an enhanced version of wideband CDMA to access the optical communication channel with huge amount of bandwidth. The OCDMA technique is very promising as it has the capability of transmitting data at 10–100 Gbps data rates. In this survey paper various optical coding schemes and incoherent and coherent OCDMA system have been discussed. It is concluded here that the different optical orthogonal coding schemes are able to generate only some of the optical orthogonal codes existing for code length '*n*' and weight '*w*' for specific values of auto correlation and cross correlation constraints λ_a and λ_c respectively.**

***Index Terms*— Optical CDMA (Code Division Multiple Access), optical orthogonal codes, Incoherent OCDMA, Coherent OCDMA.**

I. Introduction

In the present age of globalization, people are coming closer through different mediums of communications. These mediums of communications need to transfer data at high data rates and error free among multiple pairs of users communicating with each other. Among all the mediums of communications available to us, optical fiber is capable providing a huge amount of bandwidth, of the order of tens of Tera-Hertz. Because of bunching of many fibers in a cable and many cables in a conduit, and many conduits in a dig, a network span is able to provide bandwidth of the order of thousands of Tera-Hertz. This poses the challenge to research community, as how utilize this available huge amount of bandwidth which is almost error free and secure.

The available huge amount of bandwidth can be shared among multiple pairs of users to communicate with each other by using one of the multiple access schemes or hybrid multiple access schemes.

A multiple access scheme is conceptually similar to multiplexing, in this. With the help of multiple access schemes a broadcast medium can be shared between multiple users using multiplexing techniques.

Mainly there are three schemes to access the fiber bandwidth.
(a) Wavelength Division Multiple Access (WDMA)
(b) Optical Time Division Multiple Access (OTDMA)
(c) Optical Code Division Multiple Access (OCDMA).

A. Wavelength Division Multiple Access (WDMA)

It is a natural approach to share the optical fiber bandwidth by assigning unique wavelengths to multiple of users as in Fig. 1. Any two consecutive wavelengths are placed at minimum wavelength spacing $\Delta\lambda$ which is determined by the whole wavelength spacing divided by number of users, *N*. It is analogous to FDMA (Frequency Division Multiple Access) in electronic domain. In FDMA, the total available bandwidth is divided into sub-channels of lower bandwidth and these sub-channels are assigned to multiple users.

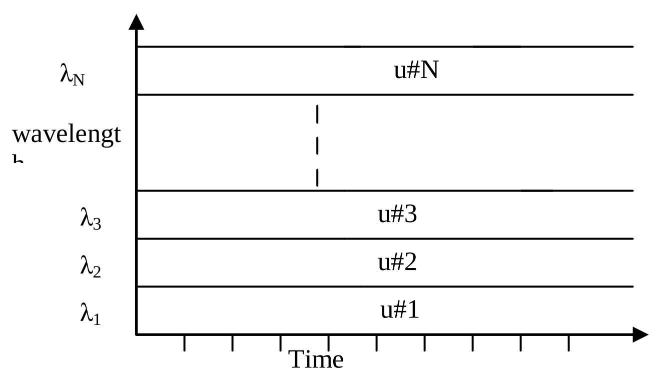

Figure 1. Allotment of N wavelengths to multiple users

The WDMA scheme has better bit error rate performance as compare to other multiple access schemes, but due to lower bound on minimum wavelength spacing limits the number of wavelengths or number of users. It's second drawback is that the attenuation caused in the optical fiber is wavelength dependent and hence attenuation is different at different wavelengths. The useful wavelengths are only those which offer lower attenuation. Hence out of *N* only wavelengths offering lower attenuation are selected for accessing the channel. It reduces total the number of users accessing the channel. Third, from security point of view this scheme has no better solution as compared to other multiple access schemes [1, 32, 33].

B. Optical Time Division Multiple Access (OTDMA)

In this scheme, all the users u#1 to u#N are assigned fixed time slots T_1 to T_N respectively as in Fig. 2. One bit period T_b is divided into N time slots and one slot is allocated to a user. Every user sends the information in the form of optical pulses to be appeared at n^{th} time slot. The width of optical pulse is not more than T_b/N. The receiver of corresponding user selects the optical pulse at the allotted time slot from all the bit periods and detect the binary information. This scheme has no multiple access interference, no channel cross-talk and the data rate is in Gbps. But the fixed allotment of time slots is wastage of bandwidth when some of the accessing users are idle for large amount of time.

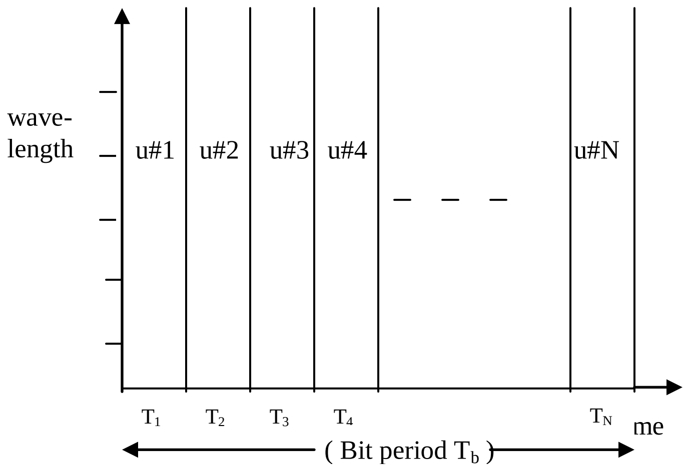

Figure 2. Time slot assignment to multiple user from bit period T_b.

This scheme has no inherent securities to processing data except using some encryption and decryption techniques which reduces the gross data rate up-to some limit. This scheme requires centralized control on all the end users so that synchronized time slot allotment could be possible. The centralized control on whole TDMA network due to the tight control on synchronization, affects network management and control worse[1,2,30,31] .

C. Optical Code Division Multiple Access(OCDMA)

The Optical CDMA is a scheme of accessing the optical channel bandwidth by multiple of users along-with their signature sequences which are orthogonal in nature, following auto-correlation and cross-correlation properties[3,4]. Here there is no fixed allotment of time slot and no fixed wavelength for particular user, in stead of it, there is a fixed code word, called signature sequence, being assigned to the particular user. This code can spread in the period Tb over '*n'* chip interval *Tc* at a single wavelength or multiple wavelength as in Figure 3a & 3b. The signature sequence of length '*n*' and weight '*w*' is composed of *w* optical pulses at the weighted positions of the orthogonal code word. The width of optical pulses is always less than T_b/n. Anyone of user, which want to access the channel, process the binary information (b/i) to the on – off keying modulator (mod) as in Figure 4, which generate an ultra short optical pulse of width less T_b/n at 0^{th} position out of *n* equal interval in the bit period T_b, in response to data bit "1'. While data bit '0' is responded by modulator (mod) as no optical pulse in bit period T_b. The signature sequence is generated at OCDMA encoder of it's particular optical transmitter (ot) by spreading the single optical pulse at 0^{th} position into *w* lines using optical splitter (OS) through *w* parallel optical delay lines of different delays determined by the weighted positions of the orthogonal code as in Figure 5a.

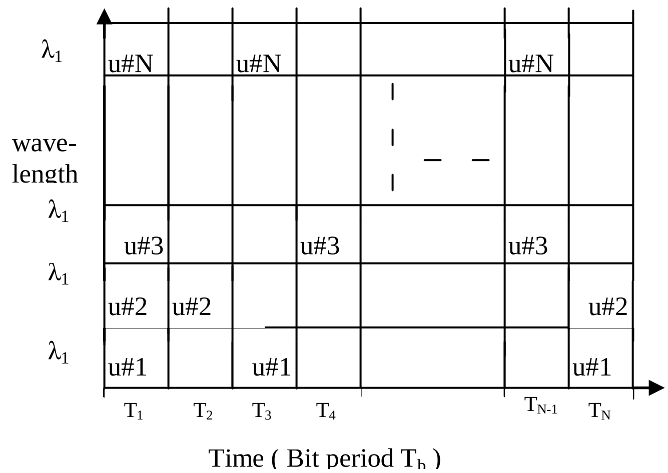

Figure 3a. One dimensional code assignment to multiple users.

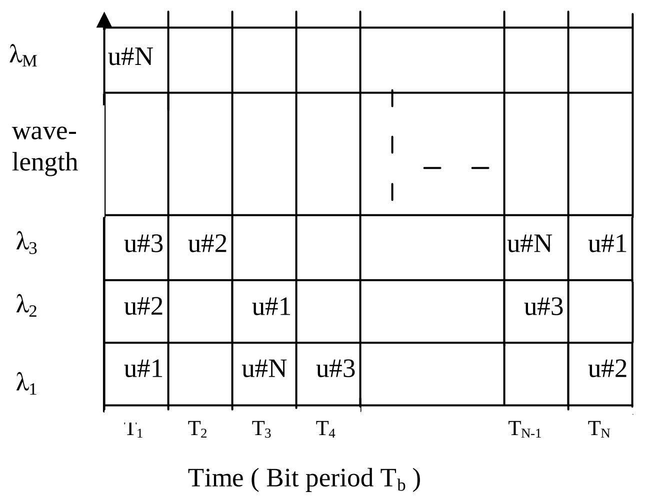

Figure 3b. Two dimensional code assignment to multiple users.

These delayed optical pulses are collected in sequence at the optical star coupler (OSC) to give output as an optical signature sequence. Similarly from other users the encoded information is collected or added in the bit period Tb and processed to the receiver by optical channel [5].

The first stage of the optical receiver (or) is optical hard limiter which makes the amplitudes of all the optical pulses at the same level in the bit period T_b. The output of optical hard limiter is processed to OCDMA decoder (Figure 5b). Every decoder is equipped with w optical delay lines in parallel similar as in OCDMA encoder. The optical delays of different lines are determined by weighted positions of the code, subtracted from the length of the code. If the corresponding signature sequence is arrived, it makes a peak of amplitude equal to the w times of normal amplitude of optical pulse in the next bit period T_b. The optical threshold device (Oth), following the decoder, compare the output in the bit period T_b. If output is greater than the threshold, a data bit '1' is detected otherwise data bit '0' is detected [5,6,7].

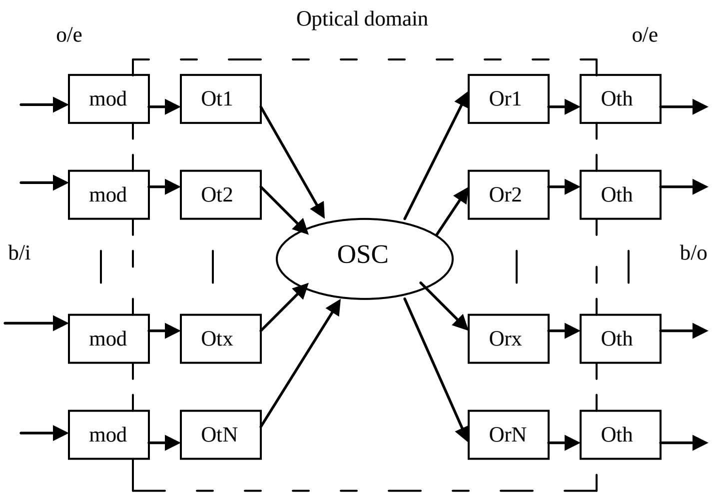

Figure 4. Optical CDMA system

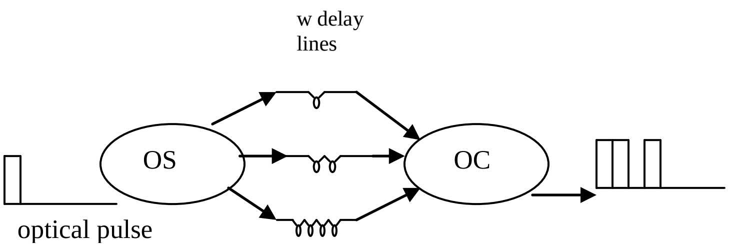

Figure 5a. Optical CDMA encoder for code length n =7, weight w =3 with weighted positions at (1,2,4)

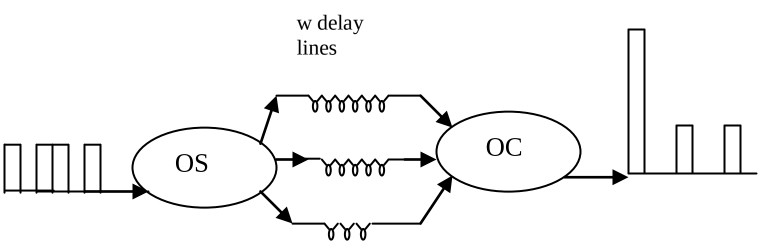

Figure 5b. Optical CDMA decoder for the code length n =7, with weight w =3 at weighted positions (1,2,4).

The OCDMA scheme has following advantages over other optical access schemes [1].

a) Optical CDMA doesn't need synchronization; hence data can be transferred in asynchronous manner which helps to simplify the network management. All users can send their information independently hence decentralized control of the network.

b) The most important property of the scheme is inherent security provided to the transmitted multiplexed signal without using any encryption coding techniques.

c) There is maximum utilization of bandwidth, with the OCDMA scheme, because multiple users can access the bandwidth with different orthogonal codes at the same time and at the same wavelength.

d) The OCDMA schemes can be one – dimensional or two – dimensional or three – dimensional as per use of Optical Orthogonal Codes (OOCs). Hence it made possible to use the OCDMA scheme with different quality of services as per requirements.
e) The Optical CDMA is more suitable with WDM for improvement of cardinality performance. It may provide better results when used in FTTH(Fiber To The Home) for providing gigabit symmetry in uplink and downlink transmission [1,8].

This Optical CDMA scheme is able to provide better results with above mentioned advantages. However a few shortcomings are also associated with this scheme [1]. The research community has to accept them as challenges to be resolved for the success of OCDMA scheme.

a) When multiple users access the same sub-channel using different optical orthogonal codes, multiplexing of codes creates some interference among the multiplexed signals. This Multiple Access Interference (MAI) is unwanted at the time of extraction of desired signal from the multiplexed signal. It increases bit error rate. To reduce this MAI, many reduction schemes are already proposed [9-22], at the cost of spectral efficiency and security performances.

b) The spectral efficiency, or the utilization factor of bandwidth offered by optical fiber, is to be maximized. Some schemes are already proposed in [23-29] to maximize the spectral efficiency, yet more research is in demand to maximize the spectral efficiency more than 1 b/s/Hz.

c) The inherent security of the Optical CDMA system, provided by the optical orthogonal codes, may be broken at any destination with the knowledge of some parameter of code used for encoding at OCDMA encoder. Hence the security is to be enhanced by some other techniques also so that information could not be decoded by unwanted users.

d) There is a requirement to create some coding schemes in such a way that it would help in reduction of MAI (Multiple Access Interference), improves the spectral efficiency and security performance.

e) The integration of OCDMA encoder and decoder on a single chip covering very small area is another issue.

f) The simplification of network management and control is an important issue in coherent type OCDMA system.

Out of all the multiple access schemes mentioned above, Optical CDMA has a bright future. The challenges offered by this scheme could be resolved to make it an ideal scheme for accessing optical fiber. As the signature sequence assigned to every user play an important role in the Optical CDMA scheme, these signature sequences are chosen from the set of optical orthogonal codes. The generation of the set of one dimensional and two dimensional optical orthogonal codes can be discussed in the next section.

II. OPTICAL CODING SCHEMES

In an Optical CDMA system, optical coding schemes play an important role, it is nothing but the backbone of OCDMA system. These schemes helps in generating the set of optical orthogonal codes, some of them are assigned to the users connected with OCDMA network. These assigned codes works as unique signature sequences for multiple users. Every user is assigned its one signature sequence. The optical orthogonal codes can be classified into following categories.

1) Uni-polar Optical Orthogonal Codes (OOCs)
2) Bipolar Optical Orthogonal Codes

1) Uni-polar Optical Orthogonal Codes

The uni-polar optical orthogonal codes are generally used in Incoherent Optical CDMA system. In optical domain, the binary digits of the code are represented by putting a short optical pulse at the weighted position or the position where binary digits are '1', while the bits '0's are represented by absence of pulse.

The uni-polar optical orthogonal codes can be categorized as

1.1 one dimensional OOCs
1.2 two dimensional OOCs

1.1) One Dimensional OOCs

An one dimensional optical orthogonal code set is characterized by (n, w, λ_a, λ_c), where n is length, w is the weight (number of '1' in the code word), λ_a is auto correlation constraint and λ_c is cross-correlation constraint. λ_a and λ_c are defined as follows.

Suppose any two code words X and Y are selected from same OOC set,

$X = (x_0, x_1, x_2, \ldots\ldots x_{n-1})$, $Y = (y_0, y_1, y_2, \ldots y_{n-1})$; $x_t, y_t \in (0,1)$

$$\lambda_a \geq \sum_{t=0}^{n-1} x_t x_{t+\tau} \text{ or } \sum_{t=0}^{n-1} y_t y_{t+\tau} \text{ for } 0<\tau \leq \text{n-1} ; \quad \text{(i)}$$

For $\tau = 0$, λ_a is equal to the weight w, which is auto-correlation peak.

$$\lambda_c \geq \sum_{t=0}^{n-1} x_t y_{t+\tau} \text{ or } \sum_{t=0}^{n-1} y_t x_{t+\tau} \text{ for } 0\leq \tau \leq \text{n-1} ; \quad \text{(ii)}$$

If $\lambda_a = \lambda_c = \lambda$; where $1 \leq \lambda \leq$ w-1,.

Then the maximum number of optical orthogonal codes, Z is given by following Johnson bounds A or B or C [34,35],

Johnson's Bound A,

$$Z(n,w,\lambda) \leq \left\lfloor \frac{1}{w} \left\lfloor \frac{n-1}{w-1} \cdots\cdots \left\lfloor \frac{n-\lambda}{w-\lambda} \right\rfloor \right\rfloor \right\rfloor = J_A(n,w,\lambda) ;$$

The Johnson's Bound B is given only when $w^2 > n\lambda$, such as,

$$Z(n,w,\lambda) \leq min(1, \left\lfloor \frac{w-\lambda}{w^2 - n\lambda} \right\rfloor) = J_B(n,w,\lambda) ;$$

The improved Johnson's Bound C is given for any integer k, $1 \leq k \leq \lambda - 1$; such that $(w-k)^2 > (n-k)(\lambda - k)$, is given as

$$Z(n,w,\lambda) \leq \left\lfloor \frac{1}{w} \left\lfloor \frac{n-1}{w-1} \cdots\cdots \left\lfloor \frac{n-(k-1)}{w-(k-1)} h \right\rfloor \right\rfloor \right\rfloor = J_C(n,w,\lambda) ;$$

Where $h = \min\left(\text{n - k}, \left\lfloor \frac{(n-k)(w-\lambda)}{(w-k)^2 - (n-k)(\lambda-k)} \right\rfloor \right)$;

$\lfloor a \rfloor$ denotes the integer value of 'a' .

There are many schemes in literature to develop the set of one dimensional optical orthogonal codes. Some of them are given below.

a) OOCs based on Prime sequences

Suppose a Galios Field GF(p) = (0,1,2,….p-1), p is a prime, is used to construct the prime sequence

$S_X^P = \{ s_x^p(0), s_x^p(1), s_x^p(2) \ldots\ldots s_x^p(p-1) \}$,

$s_x^p(j) = x.j \,(\text{mod}(P))$ for $x,j \in \text{GF}(p)$;

The binary code word $C_X^P = \{ c_x^p(0), c_x^p(1), c_x^p(2), \ldots\ldots, c_x^p(n-1) \}$ with

$$c_x^p(i) = \begin{cases} 1 & for \quad i = s_x^p(j) + jp \quad ; \quad j = 0,1,..p-1 \\ 0 & \quad otherwise \end{cases}$$

where $i = 0,1,\ldots p^2\text{-}1$

This scheme generate the set of optical orthogonal codes (n, w, λ_a, λ_c) for any prime number p, such that weight $w = p$, length $n = p^2$, auto-correlation constraint $\lambda_a = p\text{-}1$ and cross correlation constraint $\lambda_c = 2$. The number of optical orthogonal codes in the set are given by $N = p$ [36].

for example p=5,

$GF(p)$ = (0,1,2,3,4)

S_0^P = {0, 0, 0, 0, 0}, S_1^P = {0, 1, 2, 3, 4}, S_2^P = {0, 2, 4, 1,3}, S_3^P = {0, 3, 1, 4, 2}, S_4^P = {0, 4, 3, 2, 1}.

C_0^P = {10000 10000 10000 10000 10000}

C_1^P = {10000 01000 00100 00010 00001}

C_2^P = {10000 00100 00001 01000 00010}

C_3^P = {10000 00010 01000 00001 00100}

C_4^P = {10000 00001 00010 00100 01000}

b) "Quasi Prime" Optical Orthogonal Codes

This scheme is the extension of the OOC set based on prime sequences and is explained in [37]. A quasi prime code C_{xk}^{qp} is a time shifted and extended (or contracted) version of prime sequence code C_x^p. It is given as, with q number of '1's

$c_{xk}^{qp}(i) = c_x^p([i+kp]_n)$; where $i = 0,1,\ldots qp\text{-}1$

Here in code set (n, w, λ_a, λ_c)

$n = qp$, $(r\text{-}1)p<q<rp$;p is a prime number, q and r are positive integers;

weight $w = q$;
auto-correlation constraint $\lambda_a = (p\text{-}1)r$
cross-correlation constraint $\lambda_c = 2r$
and the number of code-words $N = p$;
for example p =5, q=7, k=3, with the example given as in (a), the extended version of prime codes

C_{0k}^{qp} = {10000 10000 10000 10000 10000 10000 10000}

C_{1k}^{qp} = {00010 00001 10000 01000 00100 00010 00001}

C_{2k}^{qp} = {01000 00010 10000 00100 00001 01000 00010}

C_{3k}^{qp} = {00001 00100 10000 00010 01000 00001 00100}

C_{4k}^{qp} = {00100 01000 10000 00001 00010 00100 01000}

for another example p=5, q=4, k=3, with the example given as in (a), the contracted version of prime codes

C_{0k}^{qp} = {10000 10000 10000 10000}

C_{1k}^{qp} = {00010 00001 10000 01000}

C_{2k}^{qp} = {01000 00010 10000 00100}

C_{3k}^{qp} = {00001 00100 10000 00010}

C_{4k}^{qp} = {00100 01000 10000 00001}

c) OOCs based on Quadratic Congruences

The optical orthogonal code C_X^p ={ $c_x^p(0)$, $c_x^p(1)$, $c_x^p(2)$,….., $c_x^p(p-1)$ }is based on quadratic placement operator $y_x(k)$, such that

$$c_x^p(i)=\begin{cases}1 \quad if \quad y_x(k)+kp=i \quad \bmod(p); \quad x=\{1,2,...p-1\} & and \quad k=\left\lfloor \frac{i}{p} \right\rfloor \\ 0 \quad\quad otherwise & \end{cases}$$

Here $y_x(k+1) \equiv [y_x(k)+k+1](\bmod(p))$

$$y_x(k) \equiv \frac{xk(k+1)}{2}(\bmod(p))$$

and $y_x(0) = 0$ for $0<x\leq p\text{-}1$;
here the orthogonal code set $(n, w, \lambda_a, \lambda_c)$ is constructed for the length
$n = p^2$; weight $w = p$; $\lambda_a = 2$; $\lambda_c = 4$ as in [38]
for example, p=5, the quadratic placement operators are given as
y_1^k ={0 1 3 1 0}, y_2^k ={0 2 1 2 0}, y_3^k ={0 3 4 3 0},
y_4^k ={0 4 2 4 0}, and corresponding codes are given as

C_1^5 = {10000 01000 00010 01000 10000}

C_2^5 = {10000 00100 01000 00100 10000}

C_3^5 = {10000 00010 00001 00010 10000}

C_4^5 = {10000 00001 00100 00001 10000}

The Extended Quadratic Congruence, where the length of Quadratic Congruence code is extended, can be used for construction of code of length $n = p(2p\text{-}1)$, weight $w = p$, autocorrelation constraint λ_a =1, and cross correlation constraint λ_c = 2 as explained in [39].

C_1^5 = {100000000 010000000 000100000 010000000 100000000}

C_2^5 = {100000000 001000000 010000000 001000000 100000000}

C_3^5 = {100000000 000100000 000010000 000100000 100000000}

C_4^5 = {100000000 000010000 001000000 000010000 100000000}

d) Projective Geometry based OOCs

A Projective Geometry *PG(m,q)* of order m, is constructed from a vector space *V(m+1,q)* of dimension m+1 over *GF(q)*, where *GF(q)* is Galois Field with q elements.. An s-space in a *PG(m,q)* corresponds to (*s*+1) dimensional space through the origin in *V(m+1,q)* [40]. Here one-dimensional subspaces of V are the points and the two dimensional subspaces of V are the lines.

Number of points in *PG(m,q)*, $n=\left(\frac{q^{m+1}-1}{q-1}\right)$ will give the length of the codeword

Number of points in the s-space, w= $\left(\frac{q^{s+1}-1}{q-1}\right)$ will give the weight of the codeword
The intersection of two s space is an (s-1)-space.
Number of points in the (s-1)-space,

$$\lambda = \left(\frac{q^{s}-1}{q-1}\right) = \max(\lambda_a, \lambda_c)$$

The cyclic shift of an s space is also an s-space. The orbit is the set of all s-spaces that are cyclic shift of each other. The number of code words is always equal to number of complete orbits. A codeword consists of discrete logarithm of points in each representative s-space.

Total number of s-spaces, $M_s = \binom{n}{s+1} / \binom{w}{s+1}$

Total number of codewords constructed using *PG(m,q)* for given value of s are equal to $M = \left\lfloor \frac{M_s}{n} \right\rfloor$, the code construction is explained in [40,41].
For example, m=2, q=2, then n = 7, w = q+1=3, for s=1, λ=1, the number of lines M_1=n(n-1)/w(w-1) =7 for which total number of code words M = $\lfloor M_1/n \rfloor$=1, using Galois Field GF(q^{m+1}) i.e. GF(8) and taking x^3+x^2+1 as the primitive polynomial with primitive element α, such that $\alpha^i = \beta$ to be element of GF(8) for

$0 \le i \le q^{m+1} - 2$. Here $\alpha^0 = 001$, $\alpha^1 = 010$, $\alpha^2 = 100$, $\alpha^3 = 101$, $\alpha^4 = 111$, $\alpha^5 = 011$, $\alpha^6 = 110$, with the lines of PG(2,2) with their constituent points can be given such as {(0,1,5), (0,2,3), (0,4,6), (1,2,6), (1,3,4), (2,4,5), (3,5,6)}. These lines represent to same single code with their weighted positions given by any one of the lines as above.

e) OOCs based on Error Correcting Codes

An 't' error correcting code is represented by (n,d,w), where n is length, d is minimum hamming distance between any two code words, w is the constant weight of a code from the code-set. The minimum distance $d \ge 2t+1$. An OOC $(n, w, \lambda_a, \lambda_c)$ is equivalent to constant weight error correcting codes with minimum distance $d = 2w - 2\lambda$, where λ is maximum of (λ_a, λ_c) [42-45]. Only those error correcting code are selected for optical orthogonal code set whose cyclic shifts are also code word.
for example the constant weight error correcting codes (n,d,w) = (19,4,3) can be used to generate optical orthogonal codes $(n, w, \lambda) = (19,3,1)$, here $\lambda = (2w-d)/2$. The generated optical orthogonal codes are
$C_1=(12,17,18)$, $C_2=(11,15,18)$, and $C_3=(8,16,18)$,

f) Optical orthogonal codes using Hadamard Matrix

The hadamard matrix of lowest order 2 is as given below

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \text{and}$$

The hadamard matrix of order 2n can be given as

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & \overline{H}_n \end{bmatrix}$$

$\overline{H}_n$ is complement of H_n

The possible order of hadamard matrix is 2,4, 8,16,32, 64,….
The construction of optical orthogonal codes using hadamard matrix can be studied by taking hadamard matrix of order 8 in the given example.

$$H_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}$$

the other matrix H_7 can be constructed from Hadamard matrix H_8 by deleting first row and first column, hence H_7 is

$$H_7 = \begin{bmatrix} 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Each row from H_7 can be written in form of weight set as
$R_1 = (1,3,5)$, $R_2 = (0,3,4)$, $R_3 = (2,3,6)$, $R_4 = (1,2,3)$,
$R_5 = (1,4,6)$, $R_6 = (0,5,6)$, $R_7 = (2,4,5)$.
After checking the periodicity , we find
$R_1 = R_5$; $R_2 = R_3$; $R_4 = R_6$; hence non repeated orthogonal codes are
$C_1 = 0101010$; $C_2 = 1001100$; $C_3 = 1110000$; $C_4 = 0010110$;
The generated orthogonal code set of length n = 7 ; weight $w = 3$;
$\lambda_a = 1$; $\lambda_c = 2$;

In the same way any Hadamard matrix of order n can be used to generate the matrix of order n-1 by deleting 1st row and 1st column. The rows of the matrix of order n – 1 form a code set. From the same code set the repeated or cyclically shifted codes are included only once to form the optical orthogonal code set of length $n = 4t-1$; weight $w = 2t-1$;
$\lambda_a = t-1$; $\lambda_c = t$; t is any positive integer [46].

g) Optical orthogonal codes using Skolem Sequences

The Skolem sequences of order M, can be written as collection of ordered pairs $\{ (a_i,b_i) : 1 \le i \le M, \quad b_i - a_i = i \}$ with $\bigcup_{i=1}^{M} \{a_i, b_i\} = \{1,2,.....,2M\}$. The skolem sequence of order M exist only for M = 0 (mod 4) or 1 (mod 4).
M is the number of code words and the length of code word n = 6M+1. the orthogonal codes of weight w =3 can be written as $\{x_{i1}, x_{i2}, x_{i3}\}$, x_{ij} represents the j^{th} position of bit '1' in the i^{th} code word for $1 \le i \le M$.

$x_{i1} = 0$ for all i,

$x_{i2} = i$ for all i

x_{i3} is obtained from the skolem sequence in the way such that for example skolem sequence of order $M = 5$ is given as

$S = \{ (1,2)\ (7,9)\ (3,6)\ (4,8)\ (5,10) \}$

For $i = 1$, $x_{i3} = M+2 = 7$;

For $i = 2$, $x_{i3} = M+9 = 14$;

For $i = 3$, $x_{i3} = M+6 = 11$;

For $i = 4$, $x_{i3} = M+8 = 13$;

For $i = 5$ $x_{i3} = M+10 = 15$;

The optical orthogonal code set is
{(0,1,7), (0,2,14), (0,3,11), (0,4,13), (0,5,15)}

The corresponding codes of length n =31, w=3, $\lambda_a = 1$, λ_c =1;

C_1 = (1100000010000000000000000000000)
C_2 = (1010000000000001000000000000000)
C_3 = (1001000000001000000000000000000)
C_4 = (1000100000000010000000000000000)
C_5 = (1000010000000001000000000000000)

Similarly other code words of length n =6M+1, weight w=3 and $\lambda_a = 1$, λ_c =1 can be generated using skolem sequences of order M as in [47].

h) OOCs based on table of Primes

The elements of Galois Field $GF(p)$, where p is prime, are (1,2,3,….p-1). Suppose α is a primitive root for prime p, then all the elements of $GF(p)$ can be represented by { α^x, for x = (0,1,2….p-2)}. The prime sequence codes are given as

$S_1^p = (\alpha^0, \alpha^1, \ldots\ldots, \alpha^{p-2})\text{mod}(p)$;

$S_2^p = 2S_1^p$ (mod(p)) ;

$S_3^p = 3S_1^p$ (mod(p));……… $S_{p-1}^p = (p\text{-}1)\ S_1^p$ (mod(p)).

It can be best understood by following example for p=5 and it's primitive root α =2 and $GF(5)$ = (1 2 3 4) then

2^0 = 1
2^1 = 2
2^2 = 4
2^3 = 8mod(5) =3

The prime sequence codes

S_1^p = (1 2 4 3)

S_2^p = (2 4 8 6)mod(5) = (2 4 3 1)

S_3^p = (3 6 12 9)mod(5) = (3 1 2 4)

S_4^p = (4 8 16 12)mod(5) = (4 3 1 2)

Then the orthogonal code set with weight positions is given below

C_1^p = (1 p+2 2p+4 3p+3) = (1 7 14 18)

C_2^p = (2 p+4 2p+3 3p+1) = (2 9 13 16)

C_3^p = (3 p+1 2p+2 3p+4) = (3 6 12 19)

C_4^p = (4 p+3 2p+1 3p+2) = (4 8 11 17)

The corresponding M= p-1 = 4 codes of length n = p^2-p =20, weight w = p-1= 4, $\lambda_a = 1$, λ_c = p-2 =3 will be

C_1 = (01000 00100 00001 00010) ;
C_2 = (00100 00001 00010 01000) ;
C_3 = (00010 01000 00100 00001) ;
C_4 = (00001 00010 01000 00100) ;

Similarly for other prime p and root α, the $GF(p)$, its elements, prime sequence codes and then orthogonal code set can be generated as in [47].

i) OOCs based on Number Theory

This generate the orthogonal codes (n, 3, 2, 2), for length n to be prime n = 3t+2 for some selected integer values of t and α is primitive root of n. The i^{th} codeword out of t possible code words is given by following equation

C_i = {1, $\alpha^{w+(i-1)}$, $\alpha^{2w+d+(i-1)}$ }, where $d = \lambda_c$

It can be best understood by following example of t=5, n =17, w =3, $\lambda_a = \lambda_c$ = 2. the primitive root of prime number 17 is α =3.

S_1 = (1, α^3, α^8) = (1, 10, 16)
S_2 = (1, α^4, α^9) = (1, 13, 14)
S_3 = (1, α^5, α^{10}) = (1, 5, 8)
S_4 = (1, α^6, α^{11}) = (1, 15, 7)
S_5 = (1, α^7, α^{12}) = (1, 11, 4)

The corresponding codes are

C_1 = (01000000001000001)
C_2 = (01000000000001100)
C_3 = (01000100100000000)
C_4 = (01000001000000010)
C_5 = (01001000000100000)

More details can be studied in [47].

j) Optical Orthogonal Codes based on Quadratic Residues

For any prime p, the quadratic residues (QR) a is defined as
$a = x^2$ mod(p); for any integer x
the prime 'p' has following residues (0, x_1, x_2,……., $x_{(p-1)/2}$) the QR sequence is Q_1 = (q_1, q_2, q_3,……q_p) with
$q_1 = q_p = 0$; $q_2 = q_{p-1} = x_1$; $q_3 = x_2$; and $q_k = q_{p-k+1}$ for $1 \leq k \leq p$.
the j^{th} QR sequence is obtained by multiplying Q_1 by j with all elements are given under mod(p) for j = 1 to p-1.These (p-1) QR sequence when considered as weighted positions of the binary codes with length n represents the orthogonal code set.
For example p=5, the quadratic residues are (0,1,4)
QR sequence Q_1 = (0, 1, 4, 1, 0)
QR sequence Q_2 = (0, 2, 3, 2, 0)
QR sequence Q_3 = (0, 3, 2, 3, 0)
QR sequence Q_4 = (0, 4, 1, 4, 0)
the orthogonal code set (n, w, λ_a, λ_c) = (p^2, p, 2, 2)
S_1 = (0, p+1, 2p+4, 3p+1, 4p+0) = (0, 6, 14, 16, 20)
S_2 = (0, p+2, 2p+3, 3p+2, 4p+0) = (0, 7, 13, 17, 20)
S_3 = (0, p+3, 2p+2, 3p+3, 4p+0) = (0, 8, 12, 18, 20)
S_4 = (0, p+4, 2p+1, 3p+4, 4p+0) = (0, 9, 11, 19, 20)
The corresponding code words (25, 5, 2, 2) are…
C_1 = (10000 01000 00001 01000 10000)
C_2 = (10000 00100 00010 00100 10000)
C_3 = (10000 00010 00100 00010 10000)
C_4 = (10000 00001 01000 00001 10000)
As generated in [47].

k) OOCs based on Balanced Incompleted Block Design (BIBD)

In [48], there are two families of OOC sets are constructed using BIBD. First is (n, w, 1, 1) with optimal cardinality N, the second is (n, w, 1, 2) with cardinality 2N. the code generation is described in [7,48] as follows.

a1) (n, w, 1, 1) OOC for odd w

The weight w = 2m+1 for a positive integer m, the code length n = w(w-1)t+1 for those values of t so that n be a prime number.

Consider a Galois Field $GF(n)$ with α be the primitive root of GF(n) such that values of { $log_{\alpha}[\alpha^{2mkt} - 1]$ } for $1 \le k \le m$ are all distinct with modulo m. The generated code

$$C_i = [\alpha^{mi}, \alpha^{mi+2mt}, \alpha^{mi+4mt}, ..., \alpha^{mi+4m^2t}]$$

for $i = 0$ to t-1 such that code set C_a contains (C_0, C_1, $C_2 \ldots C_{t-1}$) optical orthogonal codes.

For example w=3, t=5 which shows m=1, n=31, α=3 (primitive root of GF(31). The codes are generated as follows

$$C_0 = [1, \alpha^{10}, \alpha^{20}] = [1,25,5] = [1,5,25]$$

$$C_1 = [\alpha, \alpha^{11}, \alpha^{21}] = [3,13,15] = [3,13,15]$$

$$C_2 = [\alpha^{2}, \alpha^{12}, \alpha^{22}] = [9,8,14] = [8,9,14]$$

$$C_3 = [\alpha^{3}, \alpha^{13}, \alpha^{23}] = [27,24,11] = [11,24,27]$$

$$C_4 = [\alpha^{4}, \alpha^{14}, \alpha^{24}] = [19,10,2] = [2,10,19]$$

a2) (n, w, 1, 1) OOC for even w

The weight $w = 2m$ for a positive integer m, the code length $n = w(w\text{-}1)t\text{+}1$ to be prime for some selected values of t. the Galois Field $GF(n)$ with α be the primitive root of GF(n) such that values of { $log_{\alpha}[\alpha^{2mkt} - 1]$ } for $1 \le k \le m$ are all distinct with modulo m. The generated code

$C_i = [0, \alpha^{mi}, \alpha^{mi+2mt}, \alpha^{mi+4mt}, \ldots, \alpha^{mi+4m(m-1)t}]$ for $i = 0$ to t-1

Such that code set C_a contains (C_0, C_1, $C_2, \ldots C_{t-1}$) optical orthogonal codes.

for example w=4, t=3 which shows n=37, m=2, α=2 (primitive root of GF(37). The codes are generated as follows

$$C_0 = [0, 1, \alpha^{12}, \alpha^{24}] = [0,1,26,10] = [0,1,10,26]$$

$$C_1 = [0, \alpha^{2}, \alpha^{14}, \alpha^{26}] = [0,4,30,3] = [0,3,4,30]$$

$$C_2 = [0, \alpha^{4}, \alpha^{16}, \alpha^{28}] = [0,16,9,12] = [0,9,12,16]$$

b) (n, w, 1, 2) OOC

the code set of (n, w, 1, 2) OOC can be generated from the code set (n, w, 1, 1) OOC as follows

suppose (n, w, 1, 1) OOC code set C_a contains the codes (C_0, C_1, $C_2, \ldots C_{t-1}$). By reversing the order of bit position of all the code, the generated code words are (C_0', C_1', $C_2', \ldots C_{t-1}'$).

If $C_0 = (c_0\, c_1\, c_2\, c_3 \ldots c_{n-1})$; c_j is either 0 or 1 for j to be 0 to n-1, then $C_0' = (c_{n-1}\, c_{n-2}\, c_{n-3} \ldots c_2\, c_1\, c_0)$ similarly for others.

The code set of (n, w, 1, 2) is defined as

$C_b = (C_0, C_1, C_2, \ldots, C_{t-1}, C_0', C_1', C_2', \ldots C_{t-1}')$

for example $C_a = (C_0, C_1, C_2, C_3, C_4)$ as in part (a1)

$$C_0 = [1,5,25],\ C_1 = [3,13,15],\ C_2 = [8,9,14],$$

$$C_3 = [11,24,27],\ C_4 = [2,10,19]$$

The C_0' can be derived from C_0 as follows

$$C_0' = [n-1-25, n-1-5, n-1-1] = [5, 25, 29]$$

Similarly

$$C_1' = [15,17,27],\quad C_2' = [16,21,22],\quad C_3' = [19,6,3],$$

$$C_4' = [11,20,28]$$

The code set of (31,3,1,2) is given as

$$C_b = (C_0, C_1, C_2, C_3, C_4, C_0', C_1', C_2', C_3', C_4')$$

Table (1.1) for comparison of one dimensional optical orthogonal code (n, w, λ_a, λ_c) generation algorithms

OOC(1D) based on	Code length 'n'	Weight 'w'	Auto-correlation constraint λ_a	Cross-correlation constraint λ_c	No. of codes generated N	Other comments
Prime Sequence	p^2	p	p-1	2	p	p is a prime number
Quasi-prime	qp	q	r(p-1)	2r	p	'', (r-1)p< q<rp r,q +ve intg
Qad. Congruences	p^2	p	2	4	p-1	p is a prime
Projective Geometry PG(m, q)	$\left(\frac{q^{m+1}-1}{q-1}\right)$	$\left(\frac{q^{s+1}-1}{q-1}\right)$	$\left(\frac{q^{s}-1}{q-1}\right)$	$\left(\frac{q^{s}-1}{q-1}\right)$	Z	q is no. of elements in Galois field GF(q)
Error correcting codes	n	w	(2w-d)/2	(2w-d)/2	Z	d is min. hamming dist.
Hadamard Matrix	2^v-1	v	1	2	< n	v is +ve integer
Skolem sequences	6M+1	3	1	1	M	M is +ve intg.
Table of Prime	p^2-p	p-1	1	p-2	p-1	p is a prime
Number Theory	n =3t+2	3	2	2	t	n is a prime
Quad. residues	p^2	p	2	2	p-1	P is a prime
BIBD	$n = w(w\text{-}1)t\text{+}1$	w=2m w=2m+1	1	1,2	t	n is a prime, m +ve intg.

1.2) Two Dimensional OOCs

The two dimensional OOC can be defined with the help of array (L x N) of the family of (0,1) of constant weight size w with the maximum autocorrelation side-lobe and cross-correlation function be no more than λ_a and λ_c respectively.

Suppose the matrix codes X and Y belong to the same code set $C(L \times N, w, \lambda_a, \lambda_c)$ which follow the autocorrelation and cross correlation properties given below as in [7].

$$\sum_{i=0}^{L-1}\sum_{j=0}^{N-1} x_{i,j}\, x_{i,j\oplus\tau} \le \lambda_a \qquad \text{for } 0<\tau\le N\text{-}1$$

$$\sum_{i=0}^{L-1}\sum_{j=0}^{N-1} x_{i,j}\, y_{i,j\oplus\tau} \le \lambda_c \quad \text{for } 0 \le \tau \le N\text{-}1$$

Where $x_{i\,j}$ is an element of X at i^{th} row and j^{th} column, and $\oplus$ denotes modulo N addition.
If $\lambda = \max(\lambda_a, \lambda_c)$
The Johnson's bound A deriving maximum code size $Z(LxN, w, \lambda)$ is given in [35] as

$$Z(LxN,w,\lambda) \le \left\lfloor \frac{L}{w}\left\lfloor \frac{LN-1}{w-1} \cdots\cdots \left\lfloor \frac{LN-\lambda}{w-\lambda} \right\rfloor\right\rfloor\right\rfloor = J_A(LxN,w,\lambda);$$

The Johnson bound B is given conditionally for $w^2 > LN\lambda$,

$$Z(LxN,w,\lambda) \le \min\left(L, \left\lfloor \frac{L(w-\lambda)}{w^2 - LN\lambda} \right\rfloor\right) = J_B(LxN,w,\lambda);$$

The improved Johnson's Bound C is given for any integer k, $1 \le k \le \lambda - 1$; such that $(w-k)^2 > (LN-k)(\lambda-k)$, is given as

$$Z(LxN,w,\lambda) \le \left\lfloor \frac{L}{w}\left\lfloor \frac{LN-1}{w-1} \cdots\cdots \left\lfloor \frac{LN-(k-1)}{w-(k-1)} h \right\rfloor\right\rfloor\right\rfloor = J_C(LxN,w,\lambda);$$

Where

$$h = \min\left(LN-k, \left\lfloor \frac{(LN-k)(w-\lambda)}{(w-k)^2 - (LN-k)(\lambda-k)} \right\rfloor\right);$$

λ is called Maximum Collision Parameter (MCP) telling about maximum collisions of array elements bit '1's between any two code words.
There are so many construction schemes for the generation of 2-D OOCs are proposed in different Literatures [7, 35, 49 – 55].

a) Temporal / Spatial Addition Modulo L_T (T/S AML) codes :

In [49] the author has provided a very simple scheme for the generation of 2-dimensional optical orthogonal codes. The codes are generated on the basis of At Most – One Pulse Per Time (AM-OPPT). Suppose the code C_i is represented by a matrix with L_T rows and non-zero columns with one weighted position for each row. The weighted position is given by R_{ij} and the code C_i as

$$C_j = \begin{bmatrix} R_{0j} \\ R_{1j} \\ R_{2j} \\ \vdots \\ R_{(L_T-1)j} \end{bmatrix}$$

with $R_{0j} = 0$ for $j = 0$ to $L_T - 1$; and

$R_{ij} = (R_{(i-1)j} + j) \bmod L_T$ for $1 \le i \le L_T - 1$

If L_T is a composite number, the weight $w = L_T$, $\lambda_a = 0$, $\lambda_c = 1$, and the number of codes generated is equal to smallest prime factor of L_T . while if L_T is a prime number, the weight $w = L_T$, $\lambda_a = 0$, $\lambda_c = 1$, and the number of codes generated is equal to L_T .

For example let us suppose L_T =5 and non-zero columns is also 5 and the weight w = L_T = 5, then 5 codes are constructed as follows

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

b) Construction of (mn, λ+2, λ) Multi-Wavelength OOCs (MW-OOCs)

As described in [50], (mn, λ+2, λ) represents the set of wavelength –time matrix codes with m rows, n column, weight $w = \lambda+2$ and λ is maximum of auto-correlation constraint λ_a and cross-correlation constraint λ_c. These codes can be constructed by using one dimensional code set (m, λ+2, λ) and (n, λ+2, λ) as follows.
The number of code words in the code set (m, λ+2, λ) is given as s, where

$$s = \frac{(m-1)(m-2)(m-3)....(m-\lambda)}{(\lambda+2)!}$$

For which the set of blocks of positional weight obtained from the optical orthogonal codes, can be given as

$(a_{q0}, a_{q1}, ...a_{q(\lambda+1)})$ for $0 \le q \le s-1$

Similarly the number of code words in the set (n, λ+2, λ) are given by t, where t is

$$t = \frac{(n-1)(n-2)........(n-\lambda)}{(\lambda+2)!}$$

For which the set of blocks of positional weight obtained from the optical orthogonal codes, can be given as

$(b_{r0}, b_{r1}, ...b_{r(\lambda+1)})$ for $0 \le r \le t-1$

The positional block code set $(a_{q0}, a_{q1}, ...a_{q(\lambda+1)})$ for $0 \le q \le s-1$ has (λ+2)! distinct permutations represented by $(a_{k,q0}, a_{k,q1}, ...a_{k,q(\lambda+1)})$ for $0 \le q \le s-1$ and $0 \le k \le (\lambda+2)! - 1$

The MW- OOC sets can be constructed as follows

$$C_0 = \{(a_{k,q0} \oplus l, b_{r0}), (a_{k,q1} \oplus l, b_{r1}), ..., (a_{k,q(\lambda+1)} \oplus l, b_{r(\lambda+1)})\}$$
$$C_1 = \{(a_{k,q0} \oplus l, 0), (a_{k,q1} \oplus l, 0), ..., (a_{k,q(\lambda+1)} \oplus l, 0)\}$$
$$C_2 = \{(l, b_{r0}), (l, b_{r1}), ..., (l, b_{r(\lambda+1)})\}$$

Where $0 \le k \le (\lambda+2)! - 1$, $0 \le q \le s-1$, $0 \le r \le t-1$, and $0 \le l \le m-1$, $\oplus$ represents modulo m addition.
The cardinality C or number of code generated from above set is given as
$C = mst(\lambda+2)! + ms + mt$.
For example m=7, n=13, λ=1, w= λ+2=3.
The number of code words in code set (7,3,1) is s =1 and the code word is (0,1,3) as positional weight.
The number of code words in the code set (13,3,1) are t = 2 and code words are{ (0,1,4), (0,2,7)} as positional weight.

(a_{q0}, a_{q1}, a_{q2}) = (0,1,3) for q=0 and

(b_{r0}, b_{r1}, b_{r2}) = (0,1,4) for r =0

(b_{r0}, b_{r1}, b_{r2}) = (0,2,7) for r=1

(0,1,3) has 6 different permutations given as following {(0,1,3), (0,3,1), (1,0,3), (1,3,0), (3,0,1),(3,1,0)} for k=0 to 5 which is represented with $(a_{k,q0}, a_{k,q1}, a_{k,q2})$ for q =0.

For l =0 to 6 the code set

$C_0 = \{(a_{k,q0} \oplus l, 0), (a_{k,q1} \oplus l, 1), (a_{k,q2} \oplus l, 4)\}$ for r = 0 ,

$C'_0 = \{(a_{k,q0} \oplus l, 0), (a_{k,q1} \oplus l, 2), (a_{k,q2} \oplus l, 7)\}$ for r = 1,

$C_1 = \{(a_{0,q0} \oplus l, 0), (a_{0,q1} \oplus l, 0), (a_{0,q2} \oplus l, 0)\}$

$C_2 = \{(l, 0), (l, 1), (l, 4)\}$ for r = 0,

$C'_2 = \{(l, 0), (l, 2), (l, 7)\}$ for r = 1,

Total possible code words in this example are 7x6 + 7x6 + 7x1 + 7x1 + 7x1 = 105.

c) 2D- matrix codes from spanning ruler or optimum Golomb ruler

A spanning ruler or optimum Golomb ruler [51], is a binary (0,1) sequence of length *n* such that the distance between any two weighted bits (i.e. bit '1') is non-repetitive. The optimum Golomb ruler sequence can generate other sequences M_1 to Mp by introducing p-1 zeros in the right and cyclically right shifting 0 to p-1 times making all the sequence of same length. The length of sequence 'n' could be break into two integer factors x and y such that $n = xy$. x and y may take different values of integers to generate different matrix codes of x rows and y columns.

It can be best understood by following example as in [51].

Suppose an optimum Golomb sequence $g_1$of length 26 and weight w=7 is given as

g_1 = [11001000001000000010000101]

linearly right shifting the sequence and making it of length 32, the following M_i sequences are generated

M_1 = [11001000001000000010000101000000]
M_2 = [01100100000100000001000010100000]
M_3 = [00110010000010000000100001010000]
M_4 = [00011001000001000000010000101000]
M_5 = [00001100100000100000001000010100]
M_6 = [00000110010000010000000100001010]
M_7 = [00000011001000001000000010000101]

In matrix form the sequences M_1 to M_7 can be written in column wise taking 4 - 4 elements in the columns as

$$M_1 = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} M_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$M_3 = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} M_4 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$M_5 = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} M_6 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$M_7 = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Here by periodic shifting (column wise) we can conclude that $M_5 = M_1$; $M_6 = M_2$; $M_7 = M_3$

Hence only 4 optical orthogonal codes M_1, M_2, M_3, M_4 can be constructed.

d) 2D-wavelength/time OOCs based on Carrier Hopping Prime Code (CHPC):

The Carrier Hopping Prime Code (CHPC) set is particular type of 2D OOCs (LxN, w, λ_a, λ_c) with L=w, N= $p_1p_2...p_k$, λ_a=0 and λ_c=1. Here $p_1, p_2, p_3,. . ., p_k$ are prime numbers such that $p_k \geq p_{k-1} \geq ....p_2 \geq p_1$ and w=p_1. The codes are constructed with ordered pair as follows

$$\{[(0,0),(1, i_1 + i_2 p_1 + i_3 p_1 p_2 + ...i_k p_1 p_2......p_{k-1}),$$
$$(2, 2 \otimes_{p_1} i_1 + (2 \otimes_{p_2} i_2) p_1 + (2 \otimes_{p_3} i_3) p_1 p_2 + ... + (2 \otimes_{p_k} i_k) p_1 p_2 ... p_{k-1}), ...$$
$$...., (p_1 - 1, (p_1 - 1) \otimes_{p_1} i_1 + ((p_1 - 1) \otimes_{p_2} i_2) p_1 + ((p_1 - 1) \otimes_{p_3} i_3) p_1 p_2 + ...$$
$$.. + ((p_1 - 1) \otimes_{p_k} i_k) p_1 p_2 .... p_{k-1})]:$$
$$i_1 \in [0, p_1 - 1], i_2 \in [0, p_2 - 1], ..., i_k \in [0, p_k - 1]\}$$

where $\otimes_{p_j}$ denotes a modulo- p_j multiplication for j = {1, 2, 3, …, k, resulting in $p_1p_2...p_k$ equal to N number of orthogonal matrices.

For example, L=w=p_1=3, N=$p_1p_2p_3$ = 3x3x5

$i_1 = (0,1,2), i_2 = (0,1,2), i_3 = (0,1,2,3,4)$

The codes are constructed with ordered pair as follows

$$[(0,0),(1, i_1 + 3i_2 + 9i_3),(2, 2 \otimes_3 i_1 + (2 \otimes_3 i_2)3 + (2 \otimes_5 i_3)9]$$

e) Multiple wavelength OOCs under prime sequence permutations

Suppose a Galios Field GF(p) = (0,1,2,….p-1), p is a prime, can be used to construct the prime sequence

S_X^P ={ $s_x^p(0), s_x^p(1), s_x^p(2) ...... s_x^p(p-1)$},

$s_x^p(j)$ =x.j (mod(P)) for x,j $\in$ GF(p);

For GF(7) = (0,1,2,3,4,5,6), the prime sequences

$s_x^p(0)$ = (0,0,0,0,0,0,0);

$s_x^p(1)$ = (0,1,2,3,4,5,6);

$s_x^p(2)$ = (0,2,4,6,1,3,5);

$s_x^p(3)$ = (0,3,6,2,5,1,4);

$s_x^p(4)$ =(0,4,1,5,2,6,3);

$s_x^p(5)$ = (0,5,3,1,6,4,2);

$s_x^p(6) = (0,6,5,4,3,2,1)$;

The one dimensional optical orthogonal code can be converted into two dimensional OOCs as, suppose the code for (7,3,1,1) is given as (1101000). Using the prime sequence $s_x^p(0)$, $s_x^p(1)$ ……. $s_x^p(6)$ with only their first three (w=3) weighing positions, the following group $G_0, G_1, \ldots\ldots\ G_6$ of codes can be constructed for wavelength $\lambda_0, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6$ as

$G_0 = \{[\lambda_0\ \lambda_0\ 0\ \lambda_0\ 0\ 0\ 0], [\lambda_1\ \lambda_1\ 0\ \lambda_1\ 0\ 0\ 0],$
$[\lambda_2\ \lambda_2\ 0\ \lambda_2\ 0\ 0\ 0], [\lambda_3\ \lambda_3\ 0\ \lambda_3\ 0\ 0\ 0],$
$[\lambda_4\ \lambda_4\ 0\ \lambda_4\ 0\ 0\ 0], [\lambda_5\ \lambda_5\ 0\ \lambda_5\ 0\ 0\ 0], [\lambda_6\ \lambda_6\ 0\ \lambda_6\ 0\ 0\ 0]\}$

$G_1 = \{[\lambda_0\ \lambda_1\ 0\ \lambda_2\ 0\ 0\ 0], [\lambda_1\ \lambda_2\ 0\ \lambda_3\ 0\ 0\ 0],$
$[\lambda_2\ \lambda_3\ 0\ \lambda_4\ 0\ 0\ 0], [\lambda_3\ \lambda_4\ 0\ \lambda_5\ 0\ 0\ 0],$
$[\lambda_4\ \lambda_5\ 0\ \lambda_6\ 0\ 0\ 0], [\lambda_5\ \lambda_6\ 0\ \lambda_0\ 0\ 0\ 0], [\lambda_6\ \lambda_0\ 0\ \lambda_1\ 0\ 0\ 0]\}$

$G_2 = \{[\lambda_0\ \lambda_2\ 0\ \lambda_4\ 0\ 0\ 0], [\lambda_1\ \lambda_3\ 0\ \lambda_5\ 0\ 0\ 0], [\lambda_2\ \lambda_4\ 0\ \lambda_6\ 0\ 0\ 0],$
$[\lambda_3\ \lambda_5\ 0\ \lambda_0\ 0\ 0\ 0], [\lambda_4\ \lambda_6\ 0\ \lambda_1\ 0\ 0\ 0], [\lambda_5\ \lambda_0\ 0\ \lambda_2\ 0\ 0\ 0],$
$[\lambda_6\ \lambda_1\ 0\ \lambda_3\ 0\ 0\ 0]\}$

$G_3 = \{[\lambda_0\ \lambda_3\ 0\ \lambda_6\ 0\ 0\ 0], [\lambda_1\ \lambda_4\ 0\ \lambda_0\ 0\ 0\ 0], [\lambda_2\ \lambda_5\ 0\ \lambda_1\ 0\ 0\ 0],$
$[\lambda_3\ \lambda_6\ 0\ \lambda_2\ 0\ 0\ 0], [\lambda_4\ \lambda_0\ 0\ \lambda_3\ 0\ 0\ 0], [\lambda_5\ \lambda_1\ 0\ \lambda_4\ 0\ 0\ 0],$
$[\lambda_6\ \lambda_2\ 0\ \lambda_5\ 0\ 0\ 0]\}$

$G_4 = \{[\lambda_0\ \lambda_4\ 0\ \lambda_1\ 0\ 0\ 0], [\lambda_1\ \lambda_5\ 0\ \lambda_2\ 0\ 0\ 0], [\lambda_2\ \lambda_6\ 0\ \lambda_3\ 0\ 0\ 0],$
$[\lambda_3\ \lambda_0\ 0\ \lambda_4\ 0\ 0\ 0], [\lambda_4\ \lambda_1\ 0\ \lambda_5\ 0\ 0\ 0], [\lambda_5\ \lambda_2\ 0\ \lambda_6\ 0\ 0\ 0],$
$[\lambda_6\ \lambda_3\ 0\ \lambda_0\ 0\ 0\ 0]\}$
$G_5 = \{[\lambda_0\ \lambda_5\ 0\ \lambda_3\ 0\ 0\ 0], [\lambda_1\ \lambda_6\ 0\ \lambda_4\ 0\ 0\ 0], [\lambda_2\ \lambda_0\ 0\ \lambda_5\ 0\ 0\ 0],$
$[\lambda_3\ \lambda_1\ 0\ \lambda_6\ 0\ 0\ 0], [\lambda_4\ \lambda_2\ 0\ \lambda_0\ 0\ 0\ 0], [\lambda_5\ \lambda_3\ 0\ \lambda_1\ 0\ 0\ 0],$
$[\lambda_6\ \lambda_4\ 0\ \lambda_2\ 0\ 0\ 0]\}$
$G_6 = \{[\lambda_0\ \lambda_6\ 0\ \lambda_5\ 0\ 0\ 0], [\lambda_1\ \lambda_0\ 0\ \lambda_6\ 0\ 0\ 0], [\lambda_2\ \lambda_1\ 0\ \lambda_0\ 0\ 0\ 0],$
$[\lambda_3\ \lambda_2\ 0\ \lambda_1\ 0\ 0\ 0], [\lambda_4\ \lambda_3\ 0\ \lambda_2\ 0\ 0\ 0], [\lambda_5\ \lambda_4\ 0\ \lambda_3\ 0\ 0\ 0],$
$[\lambda_6\ \lambda_5\ 0\ \lambda_4\ 0\ 0\ 0]\}$

Here for the code (1101000) of (7,3,1,1), there are maximum 7 x 7 or (p x p) code can be constructed. If one dimensional code size is Z, then maximum $Z.p^2$ two dimensional code can be constructed [55].

The other code groups of different weight (1 to 7) can be generated in the same manner as described above.

Table (1.2) for comparison of Two dimensional Optical orthogonal code (LxN, w, λ_a, λ_c) generation algorithms

OOC (2D)	Code Array LxN	Weight 'w'	Auto-correlation constraint λ_a	Cross-correlation constraint λ_c	No. of codes generated C	Other comments
T/S AML	LxL	L	0	1	L	L is a composite number
Multi-wavelength	m x n	$\lambda+2$	λ	λ	ms+mt+mst $(\lambda+2)!$	m,n be prime, s and t no. of 1D OOC codes of length m and n respectively
Spanning Ruler or Optim. Golomb ruler	L x N > n	w	0	1	LxN-n+1	n is length of optim. Golomb seq.
BCDD and antipodal signaling	m x n	w=mn/2	λ	λ	< Z	Search method
CHPC	L=wp' N=p_1 $p_2 \ldots p_k$	w= p_1	0	1	Np'	p', p_1, $p_2, \ldots p_k$ are prime
MW OOC Prime Sequence	p x p	w < p	1	1	p x p	p is a prime

For $\lambda_a = \lambda_c = \lambda$, **Maximum Possible code**

$$Z = L(LN-1)(LN-2)\ldots(LN-\lambda)/w(w-1)\ldots(w-\lambda)$$

2) Bipolar Optical Orthogonal Codes

Generally the Coherent Optical CDMA system uses bipolar optical orthogonal codes. These codes are generated by using Maximal Length Sequences, Walsh Codes and Gold sequences as in Electronic CDMA System [7]. These provide autocorrelation peak of almost equal to length 'n' of the code and cross-correlation is almost zero which make the signal to be easily detectable. Here the weight of the code is almost half of length 'n' of the code, at which maximum possible orthogonal codes can be generated for length 'n'. These codes have almost equal number of '1' and '0'. The bit '0' is replaced by +1 and bit '1' is replaced by -1 to form bipolar codes. In **Maximum Length Sequences** [56,57], the length $n = 2^m - 1$, number of -1 are equal to $2^{m-1} - 1$ and number of +1 are equal to 2^{m-1} with maximum auto-correlation peak equal to n, while **Walsh Codes** provide maximum auto-correlation function and zero cross-correlation function [57]. The set of N+2 **Gold sequences** [57, 58] of length $N = 2^m - 1$ can be generated using a preferred pair of maximal length sequences x and y, each of length N.

These bipolar codes can be employed to vary temporal phase or spectral phase of optical pulse in time or frequency domain respectively to obtain coherent Optical CDMA signal.

The Optical CDMA can be divided into incoherent OCDMA and coherent OCDMA based on the types of codes used.

In incoherent OCDMA usually uni-polar optical orthogonal codes are used.

In coherent OCDMA usually bipolar optical orthogonal codes are used.

III. Types of Optical CDMA system

(a) Incoherent Optical CDMA system

Generally uni-polar optical orthogonal codes are employed in Incoherent OCDMA system. These uni-polar codes can be applied to the system by one dimensional, two dimensional or three dimensional spreading. In one dimensional spreading the orthogonal code is spread in temporal (time), spectral amplitude (wavelength), or spatial (fiber or optical path) dimension. In two dimensional spreading, the code is arranged in matrix form, with spreading of rows in any one of the above dimensions and columns in any other dimension. While in three dimensional spreading, the code is arranged in 3-D matrix with spreading of code in all three dimension i.e. time, wavelength, and space. On the basis of spreading of codes in one, two and three dimensions, following Incoherent coding schemes are available for Optical CDMA systems. These schemes are based on the one dimensional or two dimensional optical orthogonal codes discussed in the previous section.

Temporal Spreading

It is very first and well known coding schemes, in this scheme the bit period is divided into N chip time intervals, where N is the length of codes. The optical signature sequence is created by putting the optical pulses of equal amplitude at the weighted position (chip) by bit '1' in the code, so that number of optical pulses present in a bit period T_b are equivalent to the weight of the code as given in Figure(5a). The generated optical signal as per code is sent to the channel for data information bit '1', while the code of zero weight is sent in the bit period T_b without any optical pulses in the signal for information bit '0' [3,4]. The channel accept such signals from other transmitters to sent them simultaneously but in asynchronous manner to the receivers. The receiver accept the intermixed optical signal to extract it's authorized signal or binary information. This extraction is done by using delay lines as on the transmitter side, and the optical threshold device as already shown in figure (4,5).

Spectral Amplitude Coding (SAC)

In the SAC-OCDMA system, the source spectrum is assumed to be flat over a bandwidth and the transmitted spectrum is divided into N rectangular slices which are amplitude masked as per the orthogonal sequence of the user by the use of diffraction grating and spatial masks [59]. The coded spectrum and it's complement are propagated for transmitting the binary information '1' and '0' respectively [60]. The uni-polar codes for SAC can be generated based on Projective Geometry as given in [7] to improve the performance of the SAC-OCDMA systems. The optical encoded information as per their codes from other users is passed to the star coupler, to be sent to all active receivers through single mode optical fibers. At each receiver the information is decoded using optical splitter and optical combiners for the known optical codes [59].

Spatial Coding

The Spatial coding can be employed with temporal spreading and/or spectral amplitude coding to get two or three dimensional optical coding in multiple fiber system using fiber tapped delay lines for encoding and decoding [7]. The multimode fibers can also be employed for spatial techniques using 2D spatial masks for encoding the specific speckled patterns as code sequences [7,61]. The use of spatial coding is limited by the requirement of multiple star couplers and equal optical path length from encoder/decoder to the couplers.

Wavelength Hopping Time Spreading

The Wavelength Hopping Time Spreading (WHTS) OCDMA system uses the 2D optical orthogonal codes to spread the coded information in time and wavelength domains simultaneously. This can be explained in two ways. First, The WDM/1D-OOC codes which are generated by using a set of N optical orthogonal codes to be processed at each of the M wavelengths so that these codes can be assigned to maximum N x M users. While the 2-D WHTS codes can be generated in matrix form by following the terminology AM-OPPW (At Most – One Pulse Per Wavelength) and AM-OPPT (At Most – One Pulse Per Time). The 2D WHTS codes have better spectral efficiency as compared with WDM/1D-OOC codes [62].

The WHTS codes can be implemented by using multi-wavelength Laser source hopping from one wavelength to another very rapidly. The encoder uses *w* specific wavelengths pulses, to position them at weighted chips within bit period T_b. These WHTS encoders are based on Arrayed Waveguide Gratings (AWGs) and Thin Film Filters(TFFs) while linear array of Fiber Bragg Gratings (FBGs) based encoder require complex schemes for independently delaying each wavelength [7]. A fast WHTS encoding and decoding technique is explained in [63]. There are other schemes also for WHTS with prime codes, known as carrier hopping prime codes[64] and extended carrier hopping prime codes [65].

The function of WHTS decoder is to discriminate between desired and interfering signals by using the correlation of received signal with authentic WHTS signature sequence or matrix code . If received signal is matched with authentic matrix code at each wavelength, the autocorrelation peak reaches upto w times the amplitude of any one optical pulse used in the code. While the unmatched matrix code generate the Multiple Access Interference (MAI) at the correlator output. The WHTS decoders can also implemented using AWGs and TFFs [7].

(b) Coherent Optical CDMA System

In coherent optical CDMA systems, the phase shift keying or phase coding of the optical signal field is applied to the user's signature sequence. The optical signal field is derived from highly coherent source such as mode locked laser. The coherent Optical CDMA receiver section has to be synchronous with transmitter section so as coherent reconstruction of user's data is possible.

This coherent transmission and reconstruction is also possible with Polarization shift keying of the optical signal field over

user's signature sequence to generate a new coherent coding scheme [66].
On the basis of coherent encoding schemes, the Coherent Optical CDMA system can be classified as follows.

1. Temporal Phase Coded Optical CDMA
2. Spectral Phase Coded Optical CDMA
3. Polarization Encoded Optical CDMA

Temporal Phase Coded Optical CDMA

In Temporal Phase Coded Optical CDMA system [67] at each encoder the mode-locked laser with short pulse capabilities, is used to generate mode locked pulses to modulate the user data steam in on-off keying, DPSK, Duobinary or any other complex modulation format [7]. The temporal phase encoder creates L pulse copies of modulated pulse output with T_c chip interval between any two consecutive pulses, in a bit period T_b.
These L pulse copies are set with a specific relative phase shift depending on the user's signature sequence. The specific relative phase shift may be determined for binary digits '1' and '0' as 0 and π respectively or M –ary phase shift keying as explained for M = 4 in [68].

To decode the information, the receiver is equipped with time domain matched filter to perform temporal correlation of the L copies of the received signal with appropriate temporal phase code. The N copies of the received signal are delayed by L delay elements, each of $j(T_C)$ delay, j = 0 to L-1, so that received signal in each chip interval is multiplied with pulse in corresponding chip interval of the temporal code and then integrated over a bit period T_b [7]. It provides the auto-correlation peak output, if temporal phase code is matched. Otherwise cross correlation output is low valued noise which is also known as multiple access interference. The output in bit period T_b is decoded as bit 1 and bit '0' by optical threshold device.

Spectral Phase Coded Optical CDMA

In Spectral Phase Coded Optical CDMA [69,70], the user data is modulated with continuous pulse output of mode locked laser by on – off keying or any other complex modulation format as in temporal phase coded optical CDMA as all users are assigned their signature sequences from a set of N element spectral phase codes. The data modulated mode locked laser output expressed in frequency domain with L copies of it at L different wavelengths, is created in a bit period T_b by using diffraction grating or Virtual Imaged Phase Array grating or Micro Ring Resonator [7], with the phase difference (0 or π) applied to each spectral elements as per binary (1,0) code of length L bits assigned to the user. In the time domain, it is equivalent to temporal broadening of mode locked laser temporal pulse output, making the encoded signal more like noise. The optical channel accepts N such encoded output, and passes it to each receiver for decoding. The decoder is employed with the same device as encoder but with conjugate spectral phase coded mask in order to recover the original signal after correlation by matched filtering (time gating) and then optical thresholding [7,69]. In [71,72], 10Gbps and 70Gbps Spectral Phase Encoded Temporal Spreading (SPECTS) OCDMA test-bed are given along with there BER performance.

Polarization Encoded Optical CDMA

In Polarization encoded Optical CDMA system, the mode locked laser pulse output is modulated with binary data in on –off or any other modulation format. The data modulated mode locked laser output in a bit period T_b is used to make it's L copies at the interval of chip duration T_C to fully cover the bit duration T_b. Each pulse in the chip period T_C is given either of two state of polarization (SOP) by Polarization Shift Keying as per the binary (0,1) optical orthogonal code assigned to the user.
All such N outputs are intermixed into single mode optical fiber to send it to all N receivers. At each receiver, the authorized polarized optical orthogonal code is generated and is used for correlation to recover original signal after optical thresholding [66].

All the Optical CDMA systems described above with different coding schemes have limited performance in terms of Bit Error Rate, Spectral Efficiency and Security Performance with number of maximum users. A lot of different schemes, techniques being proposed in the literature to reduce the probability of error, maximizing spectral efficiency and security performance with increasing the number of users. Some of them are explained in the next part of the paper.

VI. Conclusion

The field of Optical CDMA system needs a lot of work to bring it out from laboratories. An open research problem is to find out the upper boundaries for all possible one, two and three dimensional optical orthogonal codes. So that as per requirement possible orthogonal codes could be designed or selected from a big group of codes. Second, one needed to minimize multiple access interference improving bit error rate, and maximizing spectral efficiency along-with improvement in security performance and network management & control. Further, reduction of dispersion and attenuation effect of optical fibers on OCDMA signals is also required. The integration of Optical CDMA system can be done by persons working in the field of VLSI by producing Integrated devices.

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