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Development of a new code family based on SAC-OCDMA system with large cardinality for OCDMA network

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ABSTRACT

We have proposed a new Multi-Diagonal (MD) code for Spectral Amplitude – Coding Optical Code Division Multiple Access (SAC-OCDMA). Although this new MD code has many properties, one of the important properties of this code is that the cross correlation is always zero. Simplicity in code construction and flexibility in cross correlation control has made this code a compelling candidate for future OCDMA applications. The Multiple access interference (MAI) effects have been successfully and completely eliminated. Based on the theoretical analysis MD code is shown here to provide a much better performance compared to Modified Quadratic Congruence (MQC) code and Random Diagonal (RD) code. Proof-of-principle simulations of encoding with 5 and 10 users with 622 Mb/s data transmission at a BER of 10^{-12} have been successfully demonstrated together with the DIRECT detection scheme.

1. Introduction

The advantages of using Optical Code Division Multiple Access (OCDMA) techniques are to provide moderate security communication and allow multiple users to access optical network with a sharing bandwidth mechanism. Nevertheless, the performance of time-domain OCDMA systems is limited by the influence of Multi-Access Interference (MAI) [1]. In a spectral-amplitude-coding OCDMA (SAC-OCDMA) system, the effect of MAI can, in theory, be removed by utilizing codes with fixed in-phase cross-correlations [2]. Various codes have been offered [3–5] to remove the MAI effect. However, these codes suffer from various limitations one way or another. The code constructions are either with a too long code length (e.g., MDW code), or variable cross correlation (e.g., RD code). Long code length is considered disadvantageous in its implementation, since either very wide band sources or narrow filter bandwidths are required. Indeed, in these systems, the main limit on the system performance is imposed by the phase-induced intensity noise (PIIN). In OCDMA system, PIIN is related to MAI due to overlapping spectra from different users [6]. When incoherent light fields are mixed and incident upon a photo-detector, the phase noise of the fields causes an intensity noise term in the photo-detector output, labeled as PIIN [7]. PIIN arises due to mixing of two uncorrelated light fields that has identical polarization, negligible self-intensity noise and having the same spectrum and intensity. The widening of spectrum beyond the maximum electrical bandwidth and the photocurrent variance is a classic signature of PIIN occurrence. It is important to note that, MAI can be solved by electrical subtraction, but the PIIN still remains. Thus, in OCDMA systems; the inherent PIIN can severely affect the overall system performance [8]. The code design with zero cross correlation is required in OCDMA systems since these code remove the effect of MAI and suppress the effect of PIIN. The effect of PIIN is ignored and only the effects of thermal noise and shot noise are considered here due to no cross correlation between users. In this manuscript we present a novel family of codes for SAC-OCDMA systems, which gives more flexibility in the selection of the code weight and number of users. These codes can be extended in the number of users while their weight is constant; furthermore, the cross correlation remains zero. In addition, the construction of these codes is easy, compared with the previous codes. A simple method based on basic mathematics for designing the codes is offered in this paper. Direct detection of the optical signal intensity has been established as the most practical in optical communication. The paper is organized as follows. In Section 2, we review the MD code construction. Section 3 is devoted to the system performance analysis and simulation analysis. Finally, conclusions are given in Section 4.

2. MD code construction

The MD code is characterized by the following parameters (N, W, λ_c) where N is the code length (number of total chips),

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W is the code weight (chips that have a value of 1), and λ_c is the in-phase cross correlation. The Cross-correlation theorem could be defined as follows: In linear algebra, the identity matrix or unit matrix of size N is the N-by-N square matrix with ones on the main diagonal and zeros elsewhere. It is denoted by I_N, or simply by I if the size is immaterial or can be trivially determined by the context.

$$I_1 = [1], \quad I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad I_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \ldots,$$

$$I_N = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \cdots & 1 \end{bmatrix}$$

Using the notation that is sometimes used to concisely describe diagonal matrices, we can write: $I_N = diag(1, 1, \ldots, 1)$. An orthogonal matrix is a square matrix with real entries whose columns (and rows) are orthogonal unit vectors (i.e., orthogonal). Equivalently, a matrix A is orthogonal if its transpose is equal to its inverse:

$$A^T A = AA^T = I. \quad \text{Alternatively}, \ A^T = A^{-1}$$

A square matrix whose transpose is also its inverse is called an orthogonal matrix; that is, A is orthogonal if $A^TA = AA^T = I_N$, the identity matrix, i.e., $A^T = A^{-1}$.

For example, $A(N \times N)$ square matrix, A is said to be orthogonal if $AA^T = A^TA = I_{N\times N}$.

The cross-correlation theorem states that cretin sets of complementary sequences have cross-correlation functions that sum to zero by using all pairwise permutations. Here, all cross-correlation function permutations are required in order that their sum be identically equal to zero. For example, if the rows and columns of a $(K \times N)$ matrix are orthogonal and all the columns except one sum to zero, then the sum of all cross-correlations between non-identical code words is zero.

So if x_{ij} is an entry from $\boldsymbol{X}$ and y_{ij} is an entry from $\boldsymbol{Y}$, then an entry from the product $\boldsymbol{C} = \boldsymbol{XY}$ is given by $C_{ij} = \sum_{K=1}^{N} x_{iK} y_{kJ}$. For the code sequences $X = (x_1, x_2, x_3, \ldots, x_N)$ and $Y = (y_1, y_2, y_3, \ldots, y_N)$, the cross-correlation function can be represented by: $\lambda_c = \sum_{i=1}^{0} 04Ex_i y_i$. When $\lambda_c = 0$, it is considered that the code possesses zero cross correlation properties.

The matrix of the MD code consists of a $K \times N$ matrix functionally depending on the value of the number of users (K), and code weight (W). For MD code the choice of weight value is free, but should be more than $1 (W > 1)$.

2.1. MD matrix design

The following steps explain how the MD code is constructed.

Step 1: Firstly, construct a sequence of diagonal matrices using the value of the weight (W) and number of subscribers (K). According to these values, the i, j_W will be set.

Where K and W are positive integer numbers, $(i = 1, 2, 3 \ldots, i_n = K)$ are defined by the number of rows in each matrix, and $(j_W = 1, 2, 3, 4, \ldots, W)$ will represent the number of diagonal matrices.

Step 2: Based on the next equations the MD sequences will be computed for each diagonal matrix.

$$S_{i,j_W} = \begin{cases} (i_n + 1 - i), & \text{For } J_W = \text{even number} \\ i, & \text{For } J_W = \text{odd number} \end{cases} \tag{1}$$

$$S_{i,1} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix}, \ S_{i,2} = \begin{bmatrix} K \\ \vdots \\ 3 \\ 2 \\ 1 \end{bmatrix}, \ S_{i,3} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix}, \ldots\ldots, \ S_{i,W} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ \vdots \\ K \end{bmatrix} \tag{2}$$

Any elements of the $S_{i,W}$ matrices represent the position of one in $T_{i,W}$ matrices with $K \times K$ dimensions.

Where $T_{i,1} = [S_{i,1}]_{K\times K}$, $T_{i,2} = [S_{i,2}]_{K\times K}$ and $T_{i,W} = [S_{i,W}]_{K\times K}$. Therefore

$$T_{i,1} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{K\times K}, \quad T_{i,2} = \begin{bmatrix} 0 & \cdots & 0 & 1 \\ 0 & \cdots & 1 & 0 \\ \vdots & \iddots & \vdots & \vdots \\ 1 & \cdots & 0 & 0 \end{bmatrix}_{K\times K}, \ \ldots,$$

$$T_{i,W} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{K\times K} \tag{3}$$

Step 3: So, the total combination of diagonal matrices (3) represents the MD code as a matrix of power $K \times N$.

$$\text{MD} = [T_{i,1} \vdots T_{i,2} \vdots \cdots\cdots \vdots T_{i,W}]_{KxN} \tag{4}$$

$$\text{MD} = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,N} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,N} \\ a_{3,1} & a_{3,2} & \cdots & a_{3,N} \\ \vdots & \vdots & \cdots & \vdots \\ a_{i_n,1} & a_{i_n,2} & \cdots & a_{i_n,N} \end{bmatrix}_{KxN} \tag{5}$$

From the above basic matrix (5), the rows determine the number of users (K). Notice that the association between code weight (W), code length (N) and number of subscribers (K) can be expressed as:

$$N = K \times W \tag{6}$$

For example, to generate a MD code family according to the previous steps, let us say $K = 4$ and $W = 3$.

Therefore, $i = 1, 2, 3, 4$, $i_n + 1 = 5$ and $j_W = 1, 2, 3$

The diagonal matrices can be expressed as:

$$S_{i,1} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix}, \quad S_{i,2} = \begin{bmatrix} 4 \\ 3 \\ 2 \\ 1 \end{bmatrix}, \quad S_{i,3} = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix} \tag{7}$$

The MD code sequence for each diagonal matrix is shown as:

$$T_{i,1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_{4\times 4}, \quad T_{i,2} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}_{4\times 4},$$

$$T_{i,3} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_{4\times 4} \tag{8}$$

The total MD code sequence will be:

$$\text{MD} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{4\times 12} \tag{9}$$

where $K = 4$, $N = 12$.

So the codeword for each user according to the above example would be:

$$\text{codeword} = \begin{cases} \text{user1} \Rightarrow \lambda_1, \lambda_8, \lambda_9 \\ \text{user2} \Rightarrow \lambda_2, \lambda_7, \lambda_{10} \\ \text{user3} \Rightarrow \lambda_3, \lambda_6, \lambda_{11} \\ \text{user4} \Rightarrow \lambda_4, \lambda_5, \lambda_{12} \end{cases}$$

The MD code design depicts that changing matrices element in the same diagonal part will result in a constant property of zero cross correlation, and it is constructed with zero cross correlation properties, which cancels the MAI. The MD code presents more flexibility in choosing the *W, K* parameters and with a simple design to supply a large number of users compared with other codes like MQC, RD codes. Furthermore, there are no overlapping chips for different users.

Table 1 shows the code length (N), weight (W) and cross correlation value (λ_c) that is required for each code type to support only 30 users. MQC, RD codes show a shorter code length than that of MD code, and this will be discussed in further details in this paper. It will be shown that the transmission performance of MD code is significantly better than that of MQC or RD codes. This is achieved through mathematical analysis.

3. System performance analysis

3.1. Gaussian approximation

To analysis our system, Gaussian approximation is used for calculation of BER [3,4]. We have considered the effect of thermal noise (σ_{th}) and shot noise (σ_{sh}) in the photo-detector. The SNR of an electrical signal is defined as the average signal power to noise power $SNR = [I^2/\sigma^2]$. Due to the zero cross correlation property of MD code, there is no overlapping in spectra of different users. For that reason the effect of incoherent intensity noise has been ignored.

The variation of photo-detector as a result of the detection of an ideally unpolaized thermal light, which is generated by spontaneous emission, can be expressed as:

$$\sigma^2 = \sigma_{sh} + \sigma_{th} \tag{10}$$

$$\sigma^2 = 2eBI + \frac{4K_bT_nB}{R_L} \tag{11}$$

where the parameters that have been used in Eq. (11) are represented in Table 2:

Table 1
Comparison between MDW, MQC, RD and MD code for the same number of users ($K = 30$).

Code	No. of users	Weight	Code length	Cross correlation (λ_c)
MDW	30	4	90	1
MQC	30	7	49	1
RD	30	4	35	Variable cross correlation code segment
MD	30	2	60	0

Table 2
System parameters.

e	Electron charge
I	Average photocurrent
B	Noise-equivalent electrical bandwidth of the receiver
K_b	Boltzmann Constant
T_n	Absolute receiver noise temperature
R_L	Receiver load resistor

Let $C_K(i)$ denote the ith element of the Kth MD code sequences, and according to the properties of MD code, the direct detection technique can be written as:

$$\sum_{i=1}^{N} C_K(i)C_l(i) = \begin{cases} W, & \text{For } K = l \\ 0, & \text{Else} \end{cases} \tag{12}$$

The following assumptions are made [6,9]:

(a) Each light source is ideally unpolarized and its spectrum is flat over the bandwidth $[v_o - \Delta v/2, v_o + \Delta v/2]$ where v_o is the central optical frequency and Δv is the optical source bandwidth expressed in Hertz.
(b) Each power spectral component has an identical spectral width.
(c) Each user has equal power at the transmitter.
(d) Each bit stream from each user is synchronized.

The above assumptions are important for mathematical straightforwardness. Devoid of these assumptions, it is difficult to analyze the system; for example, if the power for each spectral component is not identical and each user has a different power at the receiver.

The power spectral density (PSD) of the received optical signals can be written as [10]:

$$r(v) = \frac{P_{sr}}{\Delta v}\sum_{K=1}^{K} d_K \sum_{i=1}^{N} c_K(i)rect(i) \tag{13}$$

where P_{sr} is the effective power of a broad-band source at the receiver, K is the active users and N is the MD code length, and d_K is the data bit of the Kth user, which is either "1" or "0".

The $rect(i)$ function in Eq. (13) is given by

$$\begin{aligned} rect(i) &= u\left[v - v_0 - \frac{\Delta v}{2N}(-N + 2i - 2)\right] - u\left[v - v_0 - \frac{\Delta v}{2N}(-N + 2i)\right] \\ &= u\left[\frac{\Delta v}{N}\right] \end{aligned} \tag{14}$$

where $u(v)$ is the unit step function expressed as:

$$u(v) = \begin{cases} 1, & v \geqslant 0 \\ 0, & v < 0 \end{cases} \tag{15}$$

To compute the integral of $G(v)$, let us first consider an example of the PSD (denoted by $G'(v)$ of the received superimposed signal), which is shown in Fig. 1, where $A(i)$ is the amplitude of the signal of the ith spectral slot with width of $\frac{\Delta v}{N}$.

From Eq. (13) the integration of the power spectral density at the photo-detector of the lth receiver during one period can be written as:

$$\int_0^\infty G(v)dv = \int_0^\infty \left[\frac{P_{sr}}{\Delta v}\sum_{K=1}^{K} d_K \sum_{i=1}^{N} C_K(i)C_l(i)rect(i)\right]dv \tag{16}$$

Eq. (16) can be simplified as follows:

$$\int_0^\infty G(v)dv = \frac{P_{sr}}{\Delta v}\left[\sum_{K=1}^{K} d_K.W.\frac{\Delta v}{N} + \sum_{K\neq l}^{K} d_K.0.\frac{\Delta v}{N}\right] \tag{17}$$

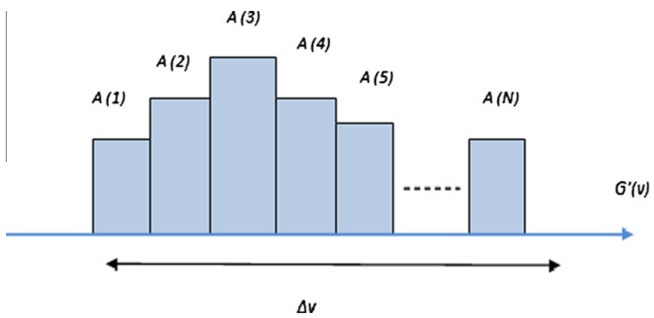

Fig. 1. The PSD of the received signal $r(v)$.

$$\int_0^\infty G(v)dv = \frac{P_{sr}}{\Delta v}\left[\sum_{K=1}^{K} d_K.W.\frac{\Delta v}{N}\right] \tag{18}$$

In the above Eq. (18), d_K is the data bit of the Kth user that is either "1" or "0".

When all users are transmitting bit "1",

$$\left[\sum_{K=1}^{K} d_K\right] = [d_1 + d_2 + d_3 + d_4 + \cdots + d_{K-1} + d_K] = W$$

As a result,

$$\int_0^\infty G(v)dV = \frac{P_{sr}W^2}{N} \tag{19}$$

The photocurrent I can be found as:

$$I = \Re\int_0^\infty G(v)dv \tag{20}$$

where $\Re$ is the responsivity of the photo-detectors given by $\Re = \frac{\eta e}{h v_c}$ [6]. Here, η is the quantum efficiency, h is Planck's constant, and v_c is the central frequency of the original broad-band optical pulse.

Then Eq.(20) can be expressed as:

$$I = \Re\int_0^\infty G(v)dv = \frac{\Re P_{sr}W^2}{N} \tag{21}$$

Substituting Eq.(21) in Eq.(11), we obtain:

$$\sigma^2 = \frac{2eB\Re P_{sr}W^2}{N} + \frac{4K_bT_nB}{R_L} \tag{22}$$

Note the probability of sending bit "1" at any time for each user is ½, thus Eq. (22) becomes

$$\sigma^2 = \frac{eB\Re P_{sr}W^2}{N} + \frac{4K_bT_nB}{R_L} \tag{23}$$

Lastly from Eq. (22) and Eq. (23) we can calculate the average SNR as:

$$\mathrm{SNR} = \left[\frac{\left(\frac{\Re P_{sr}W^2}{N}\right)^2}{\frac{eB\Re P_{sr}W^2}{N} + \frac{4K_bT_nB}{R_L}}\right] \tag{24}$$

Using Gaussian approximation, the Bit Error Rate (BER) can be expressed as [8,11]:

$$\mathrm{BER} = P_e = \frac{1}{2}erfc\left(\sqrt{\frac{\mathrm{SNR}}{8}}\right) \tag{25}$$

3.2. Spectral direct detection

Fig. 2 illustrates the block diagram of the MD code system with the direct detection technique, whereby only one pair of decoder and detector is required compared to other techniques that required two branches of inputs to the receiver like these in complementary subtraction techniques. There is also no subtraction process involved. This is achievable for the simple reason that

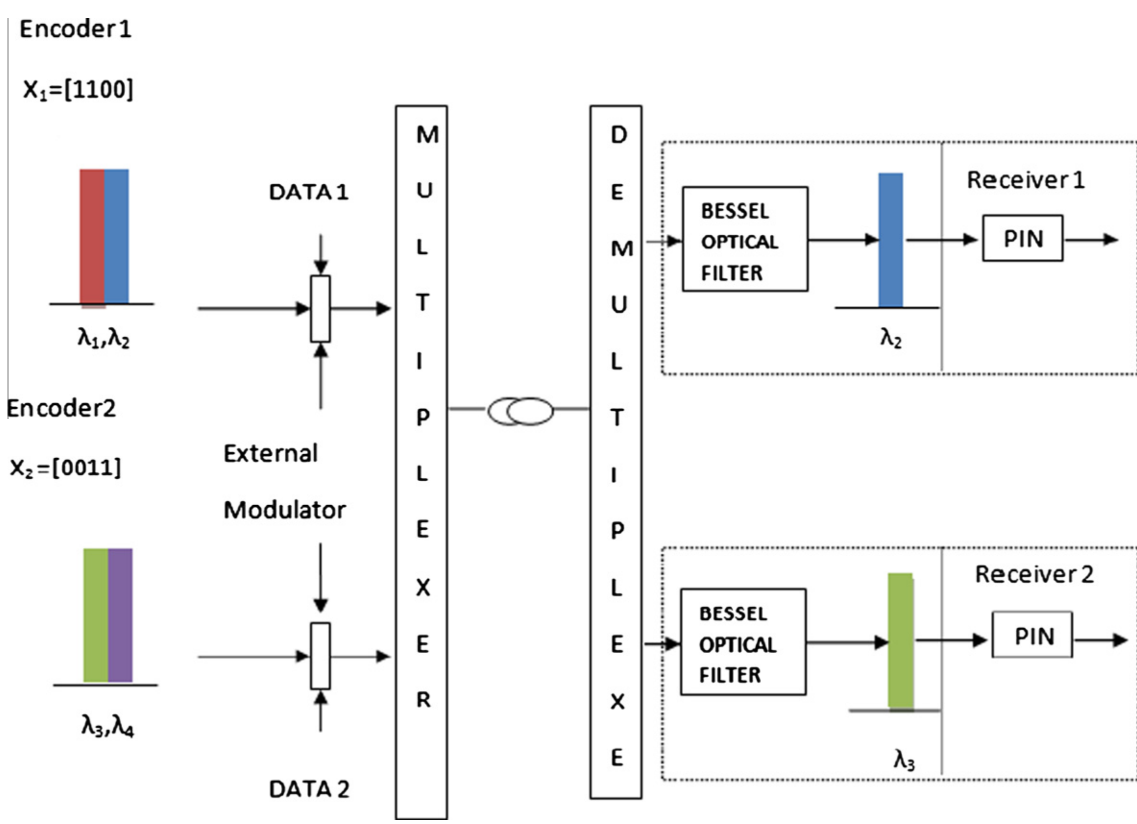

Fig. 2. Illustration of the block diagram of an MD code system with direct detection technique.

the information is assumed to be adequately recoverable for any of the chips that do not overlap any other chips from other code sequences, since MD code is designed with no overlapping chips. Thus the detector will only need to filter through the clean chips (no overlapping chips) to be directly detected by the photo diode as normal intensity modulation with the direct detection scheme. The MAI effect has been successfully and completely been eliminated because only the required signal spectra in the optical domain will be filtered. Furthermore, it is important to note that the whole spectrum still needs to be transmitted to maintain the address signature. This distinguishes the technique from Wavelength Division Multiplexing (WDM) technology.

3.3. Mathematical analysis

The performance of MD code has been compared mathematically with the recent codes, such as Modified Quadratic Congruence (MQC) and Random Diagonal (RD) [4,5] code. Using Eq. (25), the parameters used in our numerical calculation are listed in Table 3.

Fig. 3 shows the relationship between the number of simultaneous users versus the BER for the MD, RD, and MQC code for different values of K (number of active users). It is shown that the performance of the MD code is better compared to others even though the weight of other codes is equal or greater than the MD code weight. The maximum acceptable BER of 10^{-9} was achieved by the MD code with 185 active users compared to 53 active users achieved by RD code and 43 active users by MQC code. This is good considering the small value of weight used. This is evident from the fact that MD code has zero cross correlation properties with a diagonal matrix design, while RD code has an increased value of cross correlation in its code segment as the weight value increases. However, a few code-specific parameters were chosen based on the published results for these practical codes [4,5] .The calculated BER for MD code was $W = 2$, RD code $W = 4$, and $W = 14$ for MQC code.

Fig. 4 shows the system performance in terms of SNR for different code weights, $W = 6$, $W = 4$, respectively, with an electrical bandwidth $B = 311$ MHz, and $P_{sr} = -10$ dBm. Because of the non-existence of phase-induced intensity noise (PIIN) an increase in the number of simultaneous users hardly affects the system performance. Further, the scope of improvement in system performance is largely by increasing the effective power from each user at the receiver end. Moreover, it is also clear from the diagrams that an increase in code weight causes degradation in the SNR.

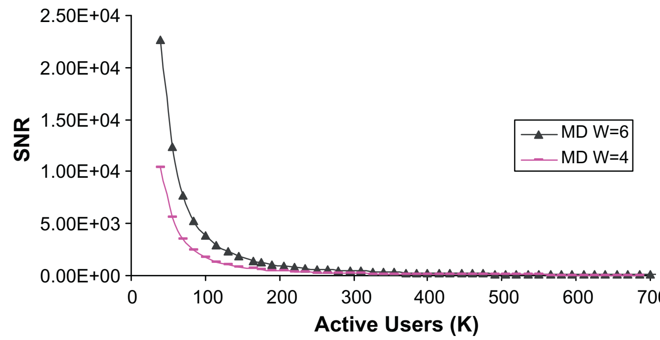

Fig. 4. SNR against the number of active users for various code weights employing the SAC-OCDMA technique.

Fig. 5 shows the variations of the BER versus the number of simultaneous users for different values of P_{sr}. In this figure, when P_{sr} is less than −25 dBm, the recent system using the MQC code will have the worst performance .This is because the larger value of the prime number code causes a larger power loss (=1/prime number) in the transmitter part. The RD code performance is better than the MQC code. This is because the RD code design has the flexibility with weight number and number of users, therefore RD code needs a smaller number of weights in comparison with the MQC code, but it has a large cross correlation value in the code segment part, which causes a reduction in code performance. Fig. 5 also shows a better performance for MD code with $P_{sr} = -10$ dBm and $P_{sr} = -20$ dBm, compared with MQC and RD code, especially when $P_{sr} = -10$ dBm. That is because of the absence of the phase-induced intensity noise (PIIN). The MD code with zero cross correlation property shows excellent performance with spectral amplitude coded asynchronous optical CDMA systems. It has been observed that stated code numbers of simultaneous users hardly affect the system performance and the scope of improvement in system performance is greater by increasing the effective power for each user at the receiver end.

Table 3
Typical parameter used in the numerical analysis calculation.

Broadband effective power	$P_{sr} = -10$ dBm
PD quantum efficiency	$\eta = 0.6$
Absolute receiver noise temperature	$T_n = 300$ K
Operating wavelength	$\lambda = 1550$ nm
Receiver load resistor	$R_L = 1030$
Electrical bandwidth	$B = 311$ MHz

3.4. Simulation analysis

The performance analysis of MD code was simulated by using the simulation software, Optisystem Version 9.0. A simple circuit design consists of five users, as illustrated in Fig. 6. Each chip has

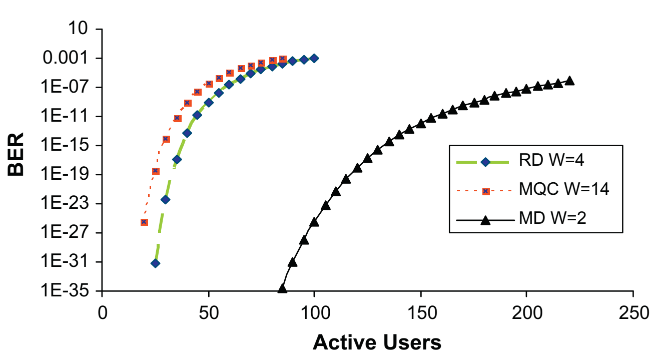

Fig. 3. BER against the number of active users for various codes employing the SAC-OCDMA technique.

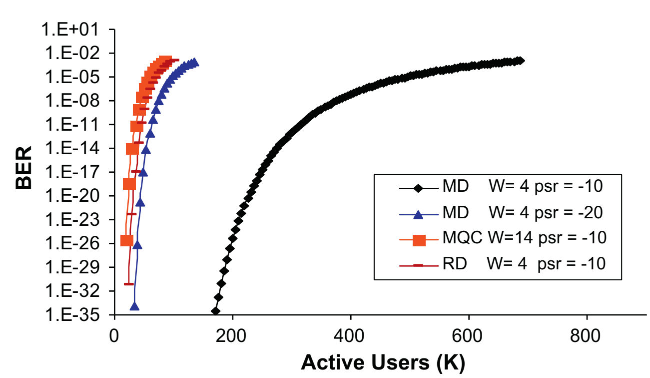

Fig. 5. BER against the number of active users when P_{sr} is different.

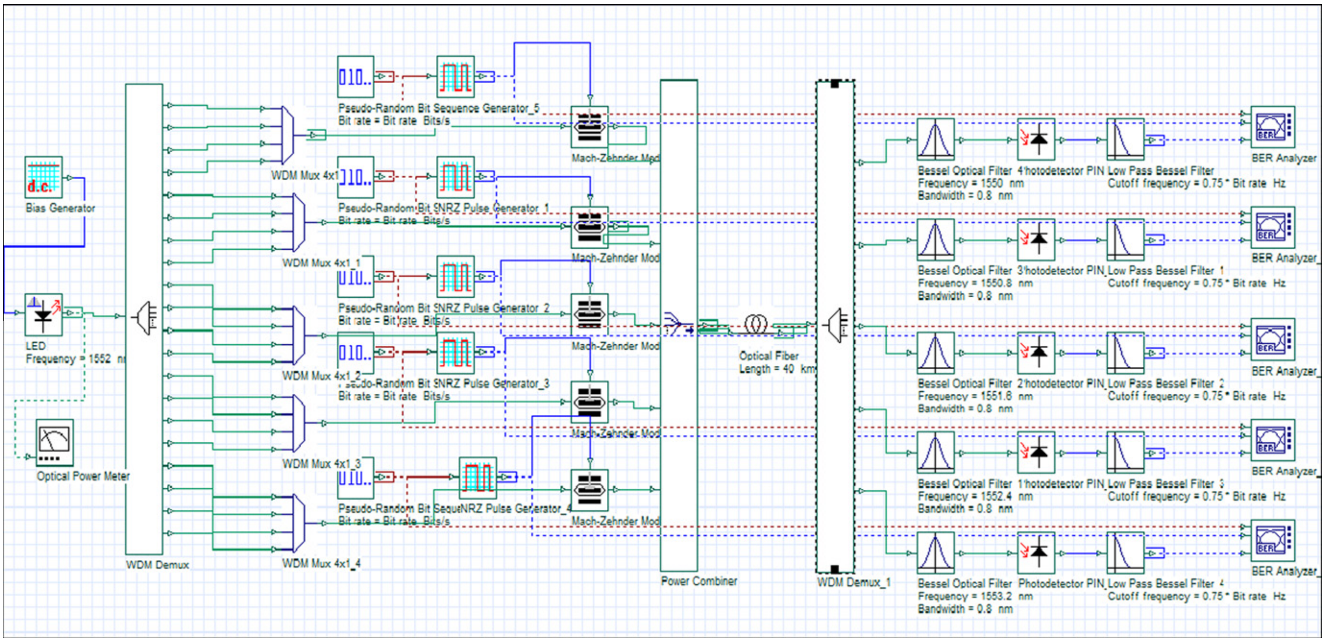

Fig. 6. MD code schematic block diagram for five users.

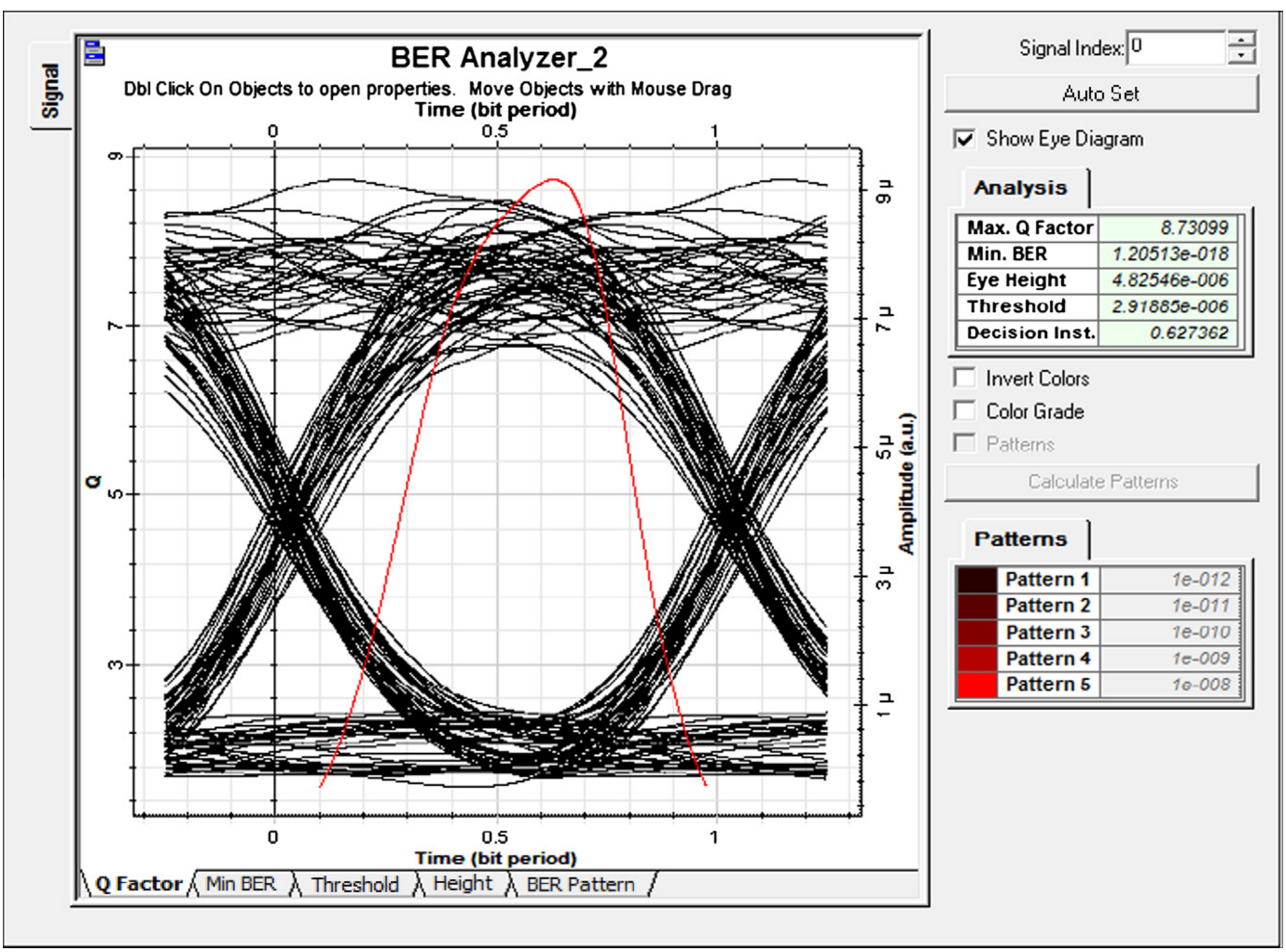

Fig. 7. Eye diagram indicating performance of five users with a weight of four using MD code.

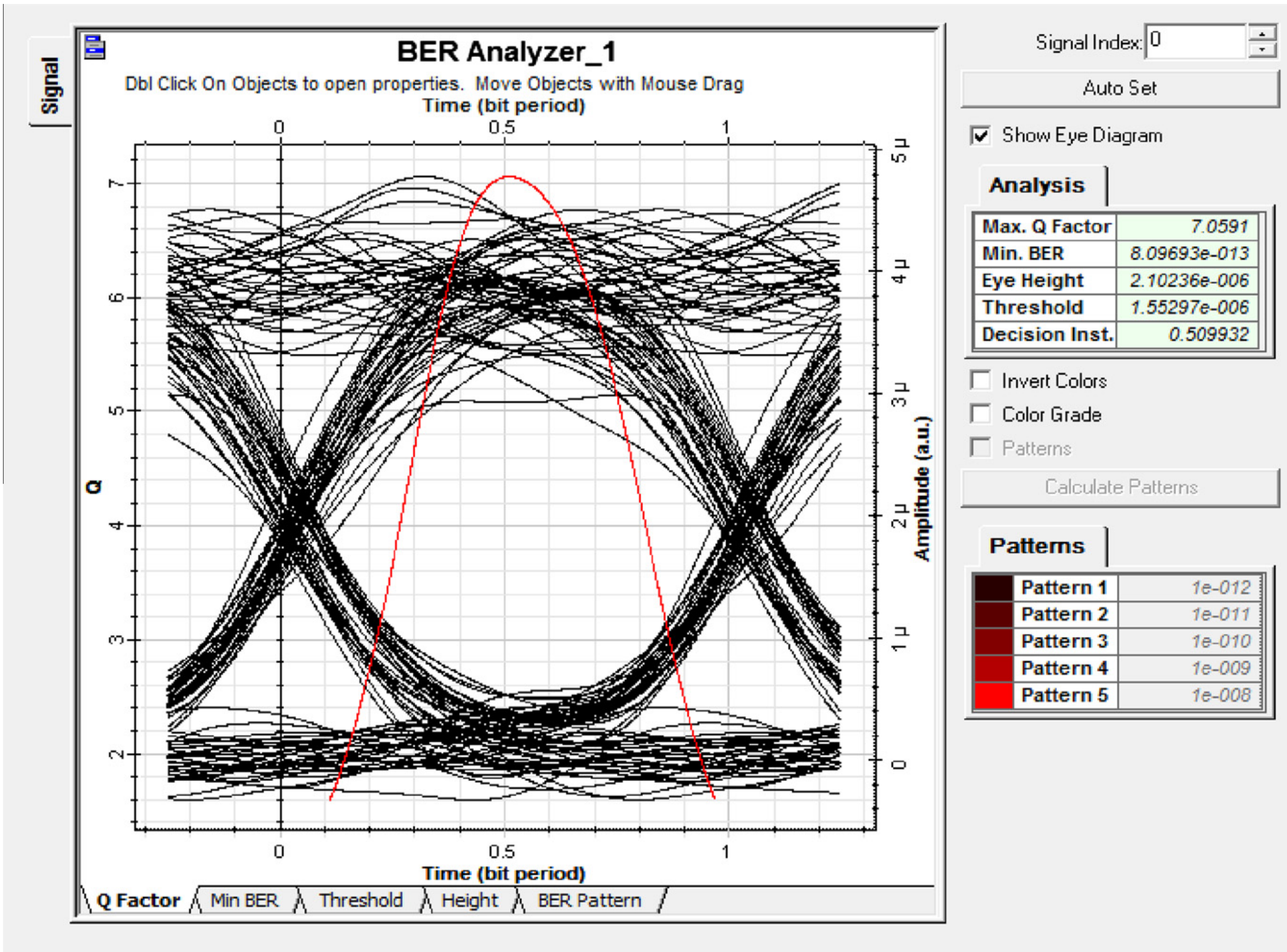

Fig. 8. Eye diagram indicating performance of 10 users with a weight of four using MD code.

a spectral width of 0.8 nm. The tests were carried out at a rate of 622 Mb/s for a 40-km distance with the ITU-T G.652 standard single-mode optical fiber (SMF). All the attenuation α (i.e., 0.25 dB/km), dispersion (i.e., 18 ps/nm km), and nonlinear effects were activated and specified according to the typical industry values to simulate the real environment as close as possible. The performances of the system were characterized by referring to the Bit Error Rate (BER). As shown in Fig. 6, after transmission we used a Demultiplexer followed by a Bassel Optical Filter spectral phase decoder operating to decode the code at the data level. The decoded signal was decoded by a photo-detector (PD) followed by a 0.75 GHz low-pass-filter (LPF). The noise generated at the receivers was set to be random and totally uncorrelated. The dark current value was 5 nA, and the thermal noise coefficient was 1.8×10^{-23} W/Hz for each of the photo-detectors. The performance of the system was characterized by referring to the BER and eye pattern. The eye pattern for MD code system as shown in Figs. 7 and 8 below, clearly show that the MD code system gave a better BER 10^{-9} as the number of users was increased. The more the eye closes, the more difficult it is to differentiate between ones and zeros in the signal. The height of the eye opening at the specified sampling time shows the noise margin or immunity to noise.

4. Conclusion

In this paper, we proposed a new code design with zero cross correlation. In the absence of the phase-induced intensity noise (PIIN) the zero cross correlation code shows excellent performance with spectral amplitude coded asynchronous optical CDMA. Based on the equations and system simulation the results of the system performance are presented. To conclude, the advantages of the code can be summarized as follows: (1) zero cross-correlation code which canceled the MAI (Multi-Access Interference); (2) flexibility in choosing W, K parameters over other codes like MQC code;(3) simple design;(4) large number of users in comparison to other codes like MQC or RD code;(5) no overlapping of spectra for different users. The performance of the system with the proposed MD code is analyzed by taking into account the effect of shot noise, and thermal noise sources. It is found that MD code is the best in terms of BER compared to MQC and RD code. Simplicity in code construction and flexibility in cross correlation control has made this code a compelling candidate for future OCDMA applications.

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