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New design of spectral amplitude coding in OCDMA with zero cross-correlation

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ABSTRACT

A zero cross-correlation (ZCC) code is proposed to reduce the impact of system impairment and multiple access interference (MAI) in spectral amplitude coding optical code division multiple access (SAC–OCDMA) system. Bit-error-rate (BER) performance is derived taking into account the effect of some noises. The key to an effective OCDMA system is the choice of efficient address codes with good or almost zero correlation properties for encoding the source. The use of ZCC code can eradicate phase induced intensity noise (PIIN) which will contribute to better BER. Thus, we demonstrate, theoretically, the performance of optical ZCC code. It is shown that optical ZCC code can accommodate more users simultaneously for the typical error rate of optical communication system of 10^{-9}. The result indicates that the established system not only preserves the capability of suppressing MAI, but also improves bit-error-rate performance as compared to the conventional coders.

1. Introduction

In OCDMA systems, MAI from all other active users is the dominating degradation and limits the number of users in the network. Therefore, one goal when designing OCDMA systems is to achieve desirable properties of the transmitted and received signals, especially, to reduce the impact of the MAI. Now, other schemes to increase the number of active users in the OCDMA system under the MAI are being studied worldwide [1]. MAI is the interference resulting from other users transmitting at the same time, which is the main effect limiting the effective BER for the overall system [2]. MAI is the main factor for performance degradation in OCDMA systems, especially when a large number of users are involved. Therefore, SAC–OCDMA system was proposed because of its ability to eliminate the influence of MAI by using codes with fixed in-phase cross-correlation [3].

In recent years, SAC scheme of optical CDMA has been introduced [4,5] to eliminate the MAI effect and preserve the orthogonality between users in the system. Several quasi-orthogonal code families are used in such SAC–OCDMA systems, such as maximal-length sequence (M-sequence) codes [6], Walsh–Hadamard codes [6,7], modified quadratic congruence (MQC) codes [4], modified double weight (MDW) [8] and so forth. The SAC–OCDMA systems assign one unique spectral amplitude codeword for each network user to code the amplitude of light source spectrum.

Noises existing in the SAC–OCDMA systems include shot noise, PIIN [7], thermal noise, and so forth. But only shot and thermal noise is considered here since PIIN is ignored due to no cross-correlation between users.

In OCDMA system, PIIN is strongly related to MAI due to overlapping spectra from different users [5]. 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 photodetector output, labeled as PIIN [9]. PIIN arises due to mixing of two uncorrelated light fields which 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, although MAI can be solved by electrical subtraction, PIIN still remains Thus, in OCDMA systems, the inherent PIIN can severely affect the overall system performance [10,11]. It will be shown later that to suppress it, the value of cross-correlation should be kept as small as possible or probably zero. Codes with ideal in-phase cross-correlation ($\lambda_c \leqslant 1$) are required in OCDMA systems since these codes eliminate multiuser interference and also suppress the effect of PIIN [12].

Direct detection of the optical signal intensity has been established as the most practical in optical communications. In direct decoding technique, only a single input to the receiver is required compared to the other techniques which require two branches of

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inputs to the receiver, for instance, the first branch represents the decoded code sequence and the second branch represents the complement of the code sequence such as in the complementary technique. The employment of the direct decoding technique will reduce the number of filters used at the receiver part.

In response, an optical ZCC code has been designed. The code structure does not have overlapping of bit ‘1’ and it will not cause the ZCC code to interfere between users and will definitely suppress PIIN. ZCC falls in a group of SAC code and only shot noise and thermal noise has been considered, ignoring PIIN due to zero cross-correlation between users. It will be discussed in detail in ‘code structure’ Section how this code has been developed to satisfy those requirements above for system impairment and MAI reduction. Direct detection technique has also been used at receiver part of this ZCC coding system due to the above mentioned advantages.

2. Code structure

The new proposed optical ZCC code is represented in a matrix $K\ X\ L$ where K rows represent the number of users and L columns represent minimum code length. These matrices have binary coefficients and a basic optical ZCC code (for weight = 1) is defined recursively in Table 1.

The ZCC code has flexibility in number of weight consideration. In order to increase the number of weights, formulation via ‘code transformation’ is required. In optical ZCC code, the basic code represents weight = 1. To transform the code from $w = 1$ to $w = 2$, the general form of transformation is given by

$$Z_T = \begin{array}{c|c} A & B \\ \hline C & D \end{array}. \tag{1}$$

where $[A]$ – consist of $(1, w(w-1))$ matrix of zero. $[B]$ – consist of w replication of matrix $\sum_{j=1}^{w} j\ [0\,1]$. $[C]$ – consist of duplication of matrix from $w-1$. $[D]$ – consist of diagonal pattern $[m \times n]$with alternate column zeros matrix $[m \times n]$. The transformation code from $w = 1 \rightarrow w = 2 \rightarrow w = 3$, for example is shown as,

$$Z_{T=1} = \begin{array}{l|c|c} & A & B \\ & \downarrow & \downarrow \\ User1 & 0 & 1 \\ \hline User2 & 1 & 0 \\ & \uparrow & \uparrow \\ & C & D \end{array}$$

$$Z_{T=2} = \begin{array}{l|ccc|ccc} & & A & & B & & \\ & & \downarrow & & \downarrow & & \\ User1 & 0 & 0 & 0 & 1 & 0 & 1 \\ \hline User2 & 0 & 1 & 0 & 0 & 1 & 0 \\ User3 & 1 & 0 & 1 & 0 & 0 & 0 \\ & & \uparrow & & \uparrow & & \\ & & C & & D & & \end{array}$$

Table 1
Basic code for ZCC.

Weight = 1		L_2	L_1
User 1	K_1	0	1
User 2	K_2	1	0

$$Z_{T=3} = \begin{array}{l|ccccccc|ccccc} & & & A & & & & & & B & & & \\ & & & \downarrow & & & & & & \downarrow & & & \\ User1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ \hline User2 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ User3 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ User4 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ & & & \uparrow & & & & & & \uparrow & & & \\ & & & C & & & & & & D & & & \end{array}$$

The relationship between the basic number of users K_B, weight w and basic code length L_B is given by;

$$K_B = w + 1 \tag{2}$$

$$L_B = w(w + 1) \tag{3}$$

When the code weight increases, the code length also increases because the cross-correlation has to be maintained at zero.

In order to increase the number of users and codes without changing the weight, a mapping technique is used as below;

$$Z_2 = \begin{bmatrix} 0 & Z_1 \\ Z_1 & 0 \end{bmatrix} = \begin{array}{cc|cc} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array}$$

$$Z_3 = \begin{bmatrix} 0 & Z_2 \\ Z_2 & 0 \end{bmatrix} = \begin{array}{cccc|cccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}$$

From the mapping, it is noted that as K increases, the code length L also increases but w is unchanged (for this particular example $w = 1$). The basic matrix is mirrored diagonally to increase K. The relationships between the mapping process m, K_m, and L_m is given by:

$$K_m = 2^m(K_B) \tag{4}$$

and

$$L_m = 2^m(L_B) \tag{5}$$

In general, the equation can be re-written as in Eq. (6) which is derived from a pattern of the code [13]:

$$\mathrm{ZCC}_{i,j} = \begin{cases} 1 \quad \text{if} \begin{cases} j = (n_1 - 1) + \lfloor (2n_1 + 1)/2 \rfloor + \sum_{m=0}^{\mathrm{imod}k_{B1}-2} (2w - 2m) \\ \quad \text{for} \quad n_1 = \{1, 2, \ldots, w - (i-1)\} \\ j = 2(i-1) + \sum_{m=1}^{\lfloor n_2 - 1 \rfloor} (2w - 2m) \\ \quad \text{for} \quad n_2 = \{1, 2, \ldots, (i-1)\} \end{cases} \\ 0 \quad \text{Otherwise} \end{cases} \tag{6}$$

Note that L also represents the spectral or the chip position in a code sequence.

For incoherent spectral coding, the source should be a broadband incoherent light source with high spectral power density which makes LED as a good candidate to be used. The LED broadband spectrum is sliced into wavelengths and for the code implementation; each user is assigned a different wavelength with

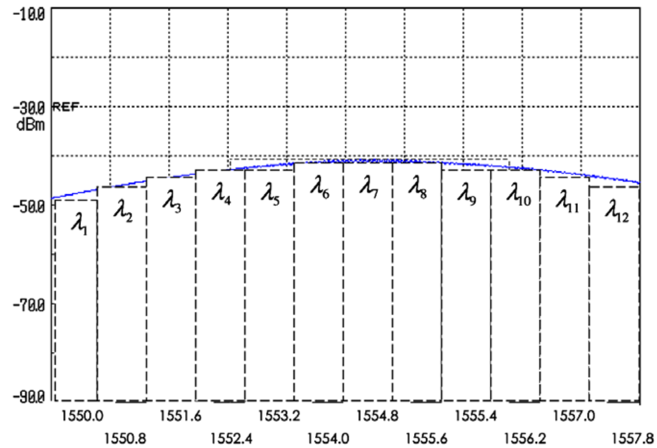

Fig. 1. Broadband spectrum sliced as a codeword.

spectral spacing equal to 0.8nm as shown in Fig. 1. The result of slicing can be translated into codeword for each user.

$$Codeword\begin{cases} User\ 1 & \Rightarrow \quad \lambda_8 \quad \lambda_{10} \quad \lambda_{12} \\ User\ 2 & \Rightarrow \quad \lambda_4 \quad \lambda_6 \quad \lambda_{11} \\ User\ 3 & \Rightarrow \quad \lambda_2 \quad \lambda_5 \quad \lambda_9 \\ User\ 4 & \Rightarrow \quad \lambda_1 \quad \lambda_3 \quad \lambda_7 \end{cases}$$

3. Performance analysis

To simplify our analysis, Gaussian approximation is used for all [5,12]. In the following analysis, we have considered the effects of both shot and thermal noises, ignoring PIIN due to the zero cross-correlation condition and no overlapping of spectra from different users (refer Table 2).

Now let $C_K(i)$ denotes the ith element of the Kth ZCC code sequence and the code properties for Direct Detection technique can be written as:

$$\sum_{i=1}^{N} C_K(i)C_l(i) = \begin{cases} W, & For \quad K = l \\ 0, & Else \end{cases} \tag{7}$$

To analyze the system with transmitter and receiver, we assume the following [5]:

(a) Each light source is ideally unpolarized and its spectrum is flat over the bandwidth $\left[v_0 - \frac{\Delta v}{2}, v_0 + \frac{\Delta v}{2}\right]$, where v_0 is the central optical frequency and is the optical source bandwidth in hertz.
(b) Each power spectral component has identical spectral width.
(c) Each user has equal power at the receiver.
(d) Each bit stream from each user is synchronized.

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

$$r(v) = \frac{P_{sr}}{\Delta V}\sum_{k=1}^{K} d_k \sum_{i=1}^{L} c_k(i)\left\{u\left[v - v_0 - \frac{\Delta v}{2L}(-L+2i-2)\right] - u\left[v - v_0 - \frac{\Delta v}{2L}(-L+2i)\right]\right\} \tag{8}$$

where P_{sr} is the effective power of a broadband source at the receiver, K is the active users and L is the ZCC code length, d_k is the data bit of the Kth user that is "1" or "0", and $u(v)$ is the unit step function.

Now, let

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

Then, integrating the PSD,

$$\int_0^\infty G_{dd}(v)dv = \int_0^\infty \left[\frac{P_{sr}}{\Delta v}\sum_{K=1}^{K} d_K \sum_{i=1}^{L} C_K(i)C_l(i)\left\{u\left[\frac{\Delta v}{L}\right]\right\}\right]dv$$

$$\int_0^\infty G_{dd}(v)dv = \frac{Psr}{\Delta v}\left[\sum_{k=1}^{k} d_k \cdot w \cdot 1 \cdot \frac{\Delta v}{L} + \sum_{k\neq l}^{k} d_k \cdot 0 \cdot 1 \cdot \frac{\Delta v}{L}\right]$$

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

When all users are transmitting bit "1", $\sum_{k=1}^{K} d_k \approx \frac{K-1+w}{L}$

$$\int_0^\infty G_{dd}(v)dv = \frac{P_{sr}[(K-1+w)w]}{L} \tag{9}$$

the photocurrent $\boldsymbol{I}$ can be expressed as:

$$I = \boldsymbol{I_{dd}} = \Re\int_0^\infty G_{dd}(v)dv$$

$$I = \Re\left[\frac{P_{sr}[(K-1+w)w]}{L}\right] \tag{10}$$

The variance of photocurrent due to the detection of an ideally unpolarized thermal light, which is generated by spontaneous emission, can be expressed as

$$\langle I^2\rangle = 2eB(I_{dd}) + \frac{4K_bT_nB}{R_L} \tag{11}$$

$$\langle I^2\rangle = 2eB\Re\left[\int_0^\infty G_{dd}(v)dv\right] + \frac{4K_bT_nB}{R_L} \tag{12}$$

From Eq. (5), when all the users are transmitting bit "1" and the probability of sending bit '1' at any time for each user is ½ [5], then Eq. (12) becomes

$$\langle I^2\rangle = \frac{P_{sr}eB\Re}{L}[(K-1+w)w] + \frac{4K_bT_nB}{R_L} \tag{13}$$

Table 2
Mapping of ZCC code and wavelength.

	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_9	λ_{10}	λ_{11}	λ_{12}
User 1	0	0	0	0	0	0	0	1	0	1	0	1
User 2	0	0	0	1	0	1	0	0	0	0	1	0
User 3	0	1	0	0	1	0	0	0	1	0	0	0
User 4	1	0	1	0	0	0	1	0	0	0	0	0
nm	1550.0	1550.8	1551.6	1552.4	1553.2	1554.0	1554.8	1555.6	1555.4	1556.2	1557.0	1557.8

By using the value of the properties in (2) and (6), the Signal to Noise ratio (SNR) of the direct detection technique can be determined using the mathematical operations as below

$$\mathrm{SNR} = \frac{(I_{dd})^2}{\langle I^2 \rangle} \tag{14}$$

When we substitute the Eqs. (10), (13) and (14) instead of I_{dd} and I, respectively the new formula of SNR will be:

$$\mathrm{SNR} = \frac{\frac{2\Re^2 P_{sr}^2 w^2}{L^2}}{\frac{P_{sr} eB\Re}{L}((K-1+w)w) + \frac{4K_b T_n B}{R_L}} \tag{15}$$

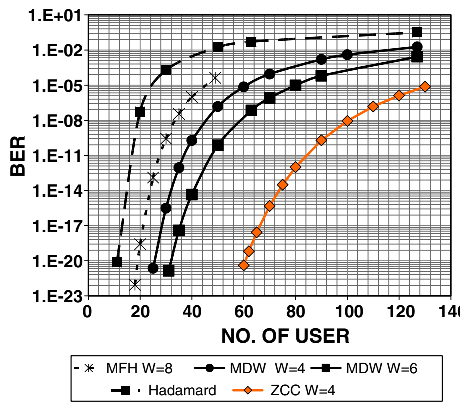

Fig. 2. Comparison BER performance for ZCC code.

Thus BER is obtained by

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{\mathrm{SNR}}{8}} \tag{16}$$

Typical parameters used in the calculation as below:

Photodetector quantum efficiency (η)	0.6
Line-width broadband source (ΔV)	3.75 THz
Operating wavelength (λ_o)	1550 nm
Electrical bandwidth (B)	311 MHz
Data bit rate (R_b)	622 Mbps
Receiver noise temperature (T_n)	300 K
Receiver load resistor (R_L)	1030 Ω

Note that Fig. 2 shows a significantly better performance from ZCC code compared to Hadamard, MDW and MFH codes. The graph also shows that at typical bit-error-rates for optical communication system ranging from 10^{-9} to 10^{-12}, 80 to 84 users can be used simultaneously. The weight used in optical ZCC code for this particular comparison is $w = 4$ with a better BER than that of MDW weight of 4 and 6.

4. Network simulation

The performance of ZCC code was simulated by using OptiSystem Version 7.0. A simple schematic block diagram consisting of 5, 10 and 20 users is illustrated in Fig. 3. Each chip has a spectral width of 0.8 nm. The tests were carried out at the rate of 622 Gbps for 30 km distance with the ITU-T G.652 standard single

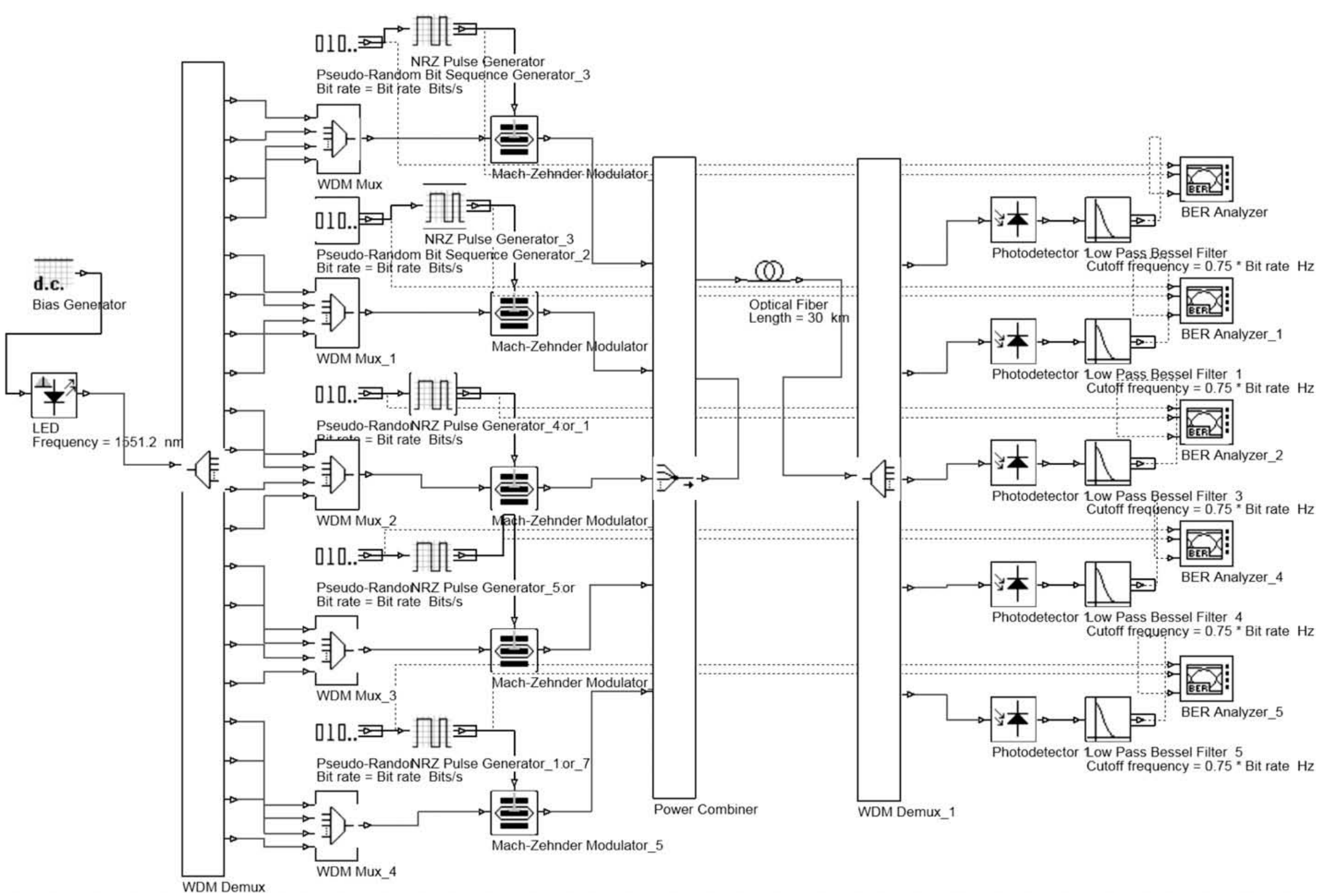

Fig. 3. Example Schematic block diagram for 5 users.

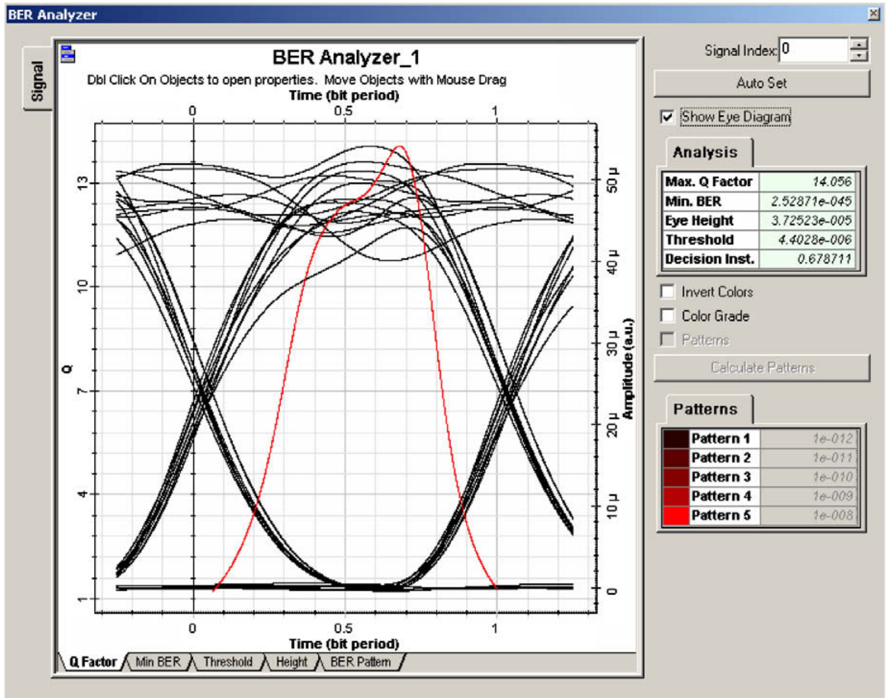

Fig. 4. Eye-diagram indicate performance of weight 4 ZCC Code for 5 users.

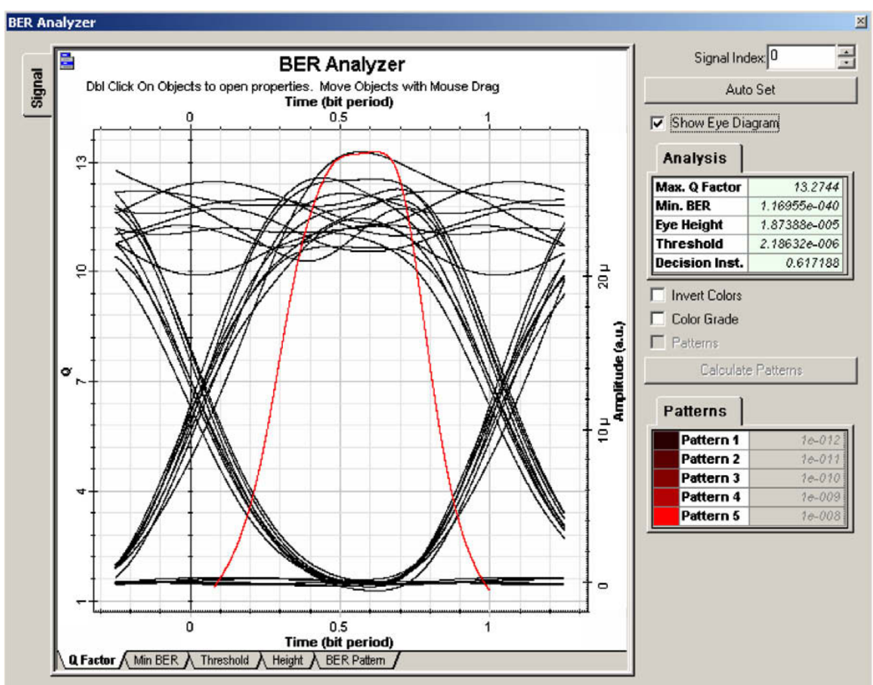

Fig. 5. Eye-diagram indicate performance of weight 4 ZCC Code for 10 users.

mode optical fiber. Attenuation of 0.2 dB/km, dispersion of 16.75 ps/nm-km and non-linear effects such as four wave mixing and self phase modulation were activated and specified according to the typical industry values to simulate the real environment as close as possible. The noises generated at the receivers are set to be random and totally uncorrelated. The dark current value is 5nA and the thermal noise coefficient is 1.0×10^{-22} W/Hz for each of the photo-detectors. The performance of the system was characterized by referring to the BER and the eye patterns. The eye patterns shown in Figs. 4–6 below clearly depict that the ZCC code system gave a better BER (less than 10^{-9}) as the number of users is increased.

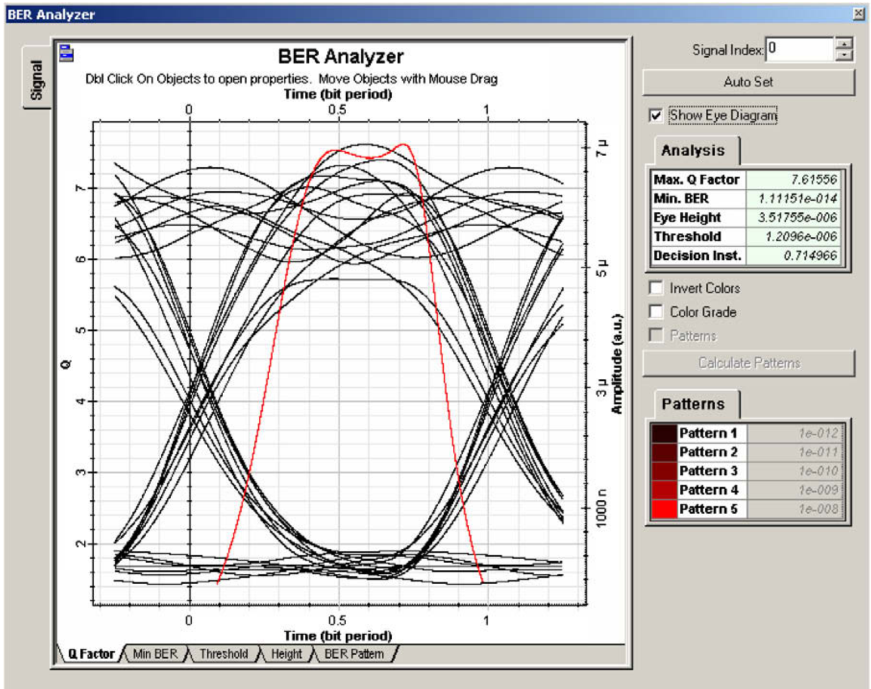

Fig. 6. Eye-diagram indicate performance of weight 4 ZCC Code for 20 users.

5. Conclusion

The performance of any OCDMA system strongly depends on the codes' properties. The most important property is the codes' cross-correlation. A code with small cross-correlation is desirable. A new variation of optical code structure for OCDMA system has been successfully developed in this paper. This code possesses numerous advantages including efficient and easy code construction, existence for every natural number of weight and the biggest advantage is being zero cross-correlation. The flexibility of ZCC code has been demonstrated whereby the basic code can be extended very easily to satisfy the demand of the users.

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