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Construction and performance analysis of a new SAC-OCDMA code based on Latin square matrix

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Abstract: In this paper a family of novel spreading code called Latin square code (LSC) is proposed for spectral amplitude coding-optical code division multiple access (SAC-OCDMA) system. The main feature of the proposed code is the zero cross-correlation which eliminates both multiple access interference (MAI) and phase induced intensity noise (PIIN). The code construction can be easily accomplished using Latin square matrix (LSM) for any weight and number of users. The simplicity in the construction code has made it a compelling candidate for future OCDMA applications. SAC-OCDMA system employing direct decoding is mathematically analyzed and then numerically simulated using Matlab and OptiSystem respectively. The results show the improvement given by the LSC code to the SAC-OCDMA system compared to the other codes such as: ZCC (zero cross-correlation) and MMS (modified multiservice) by allowing high cardinality and improving BER. Furthermore, the transmission quality, so that the BER does not exceed the value of 10^{-9}, is ensured by the LSC code with a lower effective source power of -14.5 dBm, a bit rate of 4.6 Gb/s and a cardinality exceeding ZCC and MMS by 1.7 and 1.22 times respectively. The simulation results validate the mathematical analysis and show that the system makes it possible to increase the transmission distance without affecting QoS (quality of service).

Key words: Spectral amplitude coding (SAC), optical code division multiple access (OCDMA), Latin square code (LSC), zero cross-correlation

1. Introduction

Today, the requirement of sophisticated network resources and elements is increasing rapidly due to the increasing number of users and higher bandwidth requiring applications and services. Therefore, the interest of introducing a transmission technology with a very high traffic rate is required. The electronic devices possess the upper limit on the offered maximum data rates. Thus, the fiber optic communication technology seems to be a relevant solution, and the use of code division multiple access (CDMA) technology allows an efficient exploitation of its resources [1].

Optical CDMA is a multiplexing technique where the users occupy simultaneously the same band. The basic concept is to assign a code to each transmitter that allows it to transmit information without undue interference between the users data [2].

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In order to have a high performance of OCDMA network, it is important to accommodate several users and correctly recognize the intended user's information [3]. However, The OCDMA systems suffer from several noises such as: the thermal noise, the shot noise, the phase intensity induced noise (PIIN), the dark current, and the multiple access interference (MAI) arising from other users. Of all these noises, the bit error rate (BER) is usually very vulnerable to the effect of the MAI [3, 4]. Therefore, for the performance optimization of the OCDMA communication systems, the effect of MAI must be significantly reduced. For this, different approaches have been introduced. A simple and low cost coding approach is to adopt spectral amplitude coding (SAC) to OCDMA. To remove the MAI in the SAC-OCDMA systems, 2 techniques have been used: subtraction detection techniques for fixed cross-correlation codes or direct detection technique for zero cross-correlation (ZCC) codes.

Several fixed cross-correlation codes have been investigated, such as: the optical orthogonal code (OOC) [5], the modified prime code (MPC) [6], the modified frequency hopping (MFH) code [7], the modified quadratic congruence (MQC) code [8], the Khazani-Syed (KS) code [9], the random diagonal (RD) code [10], the multi-service (MS) code [11], the dynamic cyclic shift (DCS) code [12] etc. However, these codes suffer from several limitations [13]:

- The codes are often excessively long, which makes the system difficult to implement, because it requires very wide band sources or narrow filter bandwidths.
- As the weight increases, the cross-correlation increases, resulting in a higher BER.
- Some of these codes cannot ensure the simultaneous presence of a large number of users (e.g., OOC code), a longer optical fiber distance (e.g., OOC and KS codes) or a higher bit rate (e.g., OOC and KS codes).

The use of these codes reduces the effect of the MAI but does not eliminate the PIIN. The overlap between the spectra of the different users generates a relationship between the PIIN and the MAI. When a photo-detector receives a sum of incoherent light fields, having an identical polarization, the phase noise of the fields causes a noise intensity term in the photo-detector output, called PIIN [13].

To avoid PIIN effect, the codes with zero cross-correlation have been introduced such as: the zero cross-correlation (ZCC) code [14], the new zero cross-correlation (NZCC) code [13], the single weight zero cross-correlation (SW-ZCC) code [15], the modified new zero cross-correlation (MNZCC) code [16], and the modified multiservice (MMS) code [17]. The overlapping absence between the different sequences of these codes leads to the complete elimination of MAI and PIIN. Therefore, the number of active users can be increased without needing to construct a complex receiver structure. The performances of these codes have been studied and compared with the fixed cross-correlation code families.

The main purpose of this study is to propose a novel zero cross-correlation code. The design of this code is based on the Latin square matrix, hence, the name Latin square code (LSC). Comparing with codes having the same correlation property, the proposed code presents several advantages as mentioned below:

- Flexibility to select weight parameter,
- Easy to construct,
- Supports many users with high rates of data for longer distances.

In this paper, the code construction of the proposed LSC code is described in Section 2. A schematic diagram of the SAC-OCDMA system using a direct detection technique is explained in Section 3. A mathematical analysis of the direct detection technique with the proposed code is given in Section 4. Based on MATLAB and OptiSystem simulation softwares, the discussion of the obtained results is presented in Section 5. Finally, we conclude this paper in Section 6.

2. Code construction

The LSC code is characterized by the following parameters (L, W, λ_C) where λ_C is the cross-correlation, W is the code weight (the number of chips that have a unit value), and L is the code length. The cross-correlation, of 2 different code sequences X={x_1,...,x_L} and Y={y_1,...,y_L}, is expressed as below [18]:

$$\lambda_C = \sum_{i=1}^{L} x_i y_i. \quad (1)$$

This parameter must be as low as possible to reduce the effect of the MAI. Therefore, in this work, we have proposed a new SAC-OCDMA code, which takes into account the reduction of the code length while maintaining zero cross-correlation.

The LSC code construction can be summarized by the following steps:

Step 1. Construct a Latin square matrix, M, of order W. The elements of this matrix contain W distinct numbers (between 0 and W-1) arranged in such a way that each number appearing exactly once in each row and column. For example, for $W = 3$, M can be expressed as

$$M = \begin{bmatrix} 0 & 1 & 2 \\ 1 & 2 & 0 \\ 2 & 0 & 1 \end{bmatrix}.$$

In general, each element of the matrix M can be written as

$$M(i,j) = (i+j)modW;\ 0 \le j \le (W-1), 0 \le i \le (W-1). \quad (2)$$

Step 2. The generation of the basic LSC sequences is based on the following equation

$$C_B(i,k) = \begin{cases} 1 & ; \quad k = M(i,j) + jW,\ 0 \le j \le (W-1), 0 \le i \le (W-1) \\ 0 & ; \quad otherwise \end{cases} \quad (3)$$

For $W = 3$, the basic LSC sequences are listed in Table 1.

Table 1. The basic LSC sequences for $W = 3$.

i \ k	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	1	0	0	0	1	0	0	0	1
1	0	1	0	0	0	1	1	0	0
2	0	0	1	1	0	0	0	1	0

In this case, the minimum length of the code is 9 and the number of users is 3. Thus, the code weight, the minimum code length (L_B) and the number of users (N_B) can be interrelated as follows:

$$\begin{cases} L_B = W^2 \\ N_B = W \end{cases} \tag{4}$$

Step 3. The mapping technique can be used to increase the number of users while maintaining a fixed weight. This is can be achieved by diagonally setting the basic matrix code, C_B, m times. Then, the final code matrix C is obtained as [5]

$$C = \begin{bmatrix} C_B^{(1)} & 0 & 0 & 0 & 0 \\ 0 & C_B^{(2)} & 0 & 0 & 0 \\ 0 & 0 & C_B^{(3)} & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & C_B^{(m)} \end{bmatrix}. \tag{5}$$

Here $C_B^{(x)}$ is the xth mapping element ($x = 1, 2, \ldots, m$) and each "0" in the mapping matrix is a zero matrix with the same size of C_B. Hence, for a given number of mapping, m, the length of the code and the number of users are given by

$$\begin{cases} L = m\, L_B \\ N = m\, N_B \end{cases} \tag{6}$$

For example, to increase the number of active users to 6 ($N = 6$) while maintaining $W = 3$, the matrix C_B given in Table 1 must be repeated 2 times ($m = 2$). Then, the final code matrix becomes

$$C = \begin{bmatrix} 1&0&0&0&1&0&0&0&1&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&1&1&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&1&0&0&0&1&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0&0&0&1&0&0&0&1 \\ 0&0&0&0&0&0&0&0&0&0&1&0&0&0&1&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&1&0&0&0&1&0 \end{bmatrix}.$$

In order to exploit the bandwidth of the SAC-OCDMA system by the largest number of active users, the code length must be as short as possible. Table 2 shows the comparison between different codes having the same cross-correlation property (λ_C=0). It illustrates the code length (L) and weight (W) that is required for each code to support only 80 users. It is clearly shown that the LSC code has a shorter code length compared to the other codes.

3. System description

The absence of overlap between the LSC codes (λ_C=0) eliminates MAI and PIIN. Thus, reduce the complexity of the receiver structure. Therefore, the direct detection technique is adopted to analyze the performance of this code. It contains a single decoder which has an identical spectral response to the intended encoder. This technique is very simple, less expensive and it makes it possible to detect the spectrum of the desired signal if the codes used are orthogonal.

Table 2. Comparison between the codes of the SAC-OCDMA system.

Code	Number of users (N)	Weight (W)	Code length (L)
ZCC	80	3	384
MMS	80	3	252
MNZCC	80	3	384
LSC	80	2	160
		3	248
		4	320

Figure 1 presents the SAC-OCDMA system structure based on the LSC code. At the transmitter, for each code sequence, the corresponding wavelengths are combined using an optical coupler and then modulated by an external modulator. The modulated signals from all users are then multiplexed together to send via a single-mode optical fiber (SMF). At the receiver, direct detection scheme is used. The received combined optical signal is split and decoded with respect to user's codes. Once the optical signal of the desired user is formed, it is converted to an electrical form using a photo-detector.

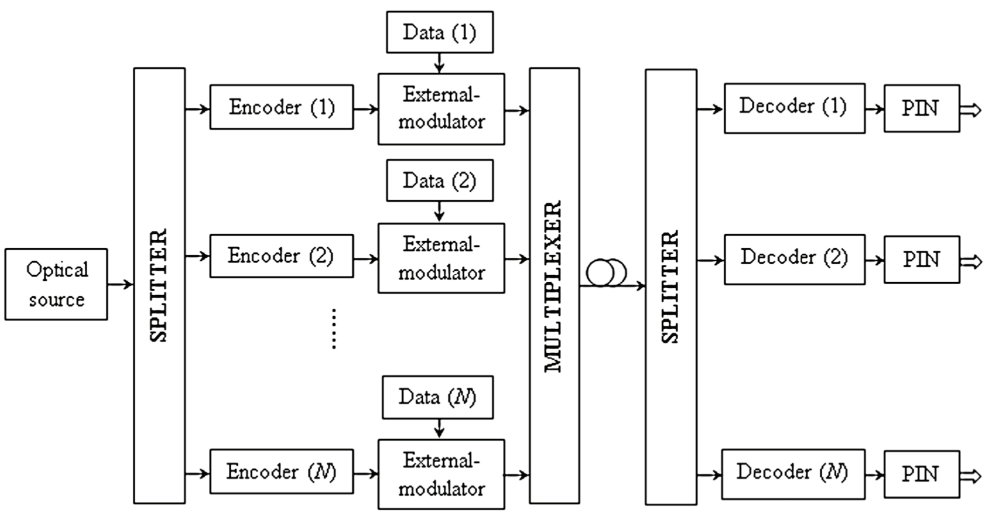

Figure 1. Block diagram of SAC-OCDMA system using the LSC code.

4. System performance

To analyze the system, the following conditions are assumed [8, 17, 19].

- N active users are considered.
- All users have the same transmit and receive powers.
- The optical source is assumed ideally unpolarized with a flat spectrum over all the bandwidth $[\nu_0 - \Delta\nu/2, \nu_0 + \Delta\nu/2]$ where ν_0 and $\Delta\nu$ are the central optical frequency and optical source bandwidth, respectively, expressed in Hz.

- The power spectral components are supposed to have the same spectral width.
- The first user is assumed to be the desired one and the synchronization is maintained at the receiver.

According to these conditions, the transmitted optical signal can be given by

$$s(t) = \sum_{k=1}^{N} s_k(t), \tag{7}$$

where $s_k(t)$ represents the signal of the kth transmitter

$$s_k(t) = P_0 d_k(t) C_k(t);\ 0 \leq t \leq T \tag{8}$$

with, P_0 means the source pulse's power, $d_k(t)$ is the kth user's binary data sequence and $C_k(t)$ is the proposed LSC code signal of the kth user. $C_k(t)$ can be written as

$$C_k(t) = \sum_{i=-\infty}^{+\infty} C_k(i)\ P_{T_c}(t - iT_c), \tag{9}$$

where $C_k(i) \in \{0,1\}$ is the ith element of the kth LSC sequence and $P_{T_c}(t)$ is a unit rectangular pulse of duration T_c.

In SAC-OCDMA system using broadband light sources with flat power spectral density (PSD), the thermal noise, the PIIN and the shot noise mainly dominate the performance. To remove PIIN, the cross-correlation value should be as small as possible [20].

Since the LSC code has zero cross-correlation property, the PIIN effect is ignored, and only the thermal noise and the shot noise impacts are considered.

The performance of an optical receiver depends on the signal to noise ratio (SNR), which is defined as $SNR = \frac{I^2}{\sigma^2}$, where I is the average photo-current and σ^2 is the variance of different noise sources. For LSC coding, σ^2 can be written as the sum of the shot noise (σ_{sh}^2) and the thermal noise (σ_t^2) [21]

$$\sigma^2 = \sigma_{sh}^2 + \sigma_t^2 = 2eIB + \frac{4K_B T_n B}{R_L}, \tag{10}$$

where, e is the electronic charge, B is the electrical bandwidth of the receiver, K_B is the Boltzmann's constant, T_n is the absolute receiver noise temperature and R_L is the receiver load resistance. In Equation 10, the shot noise is represented by the first term and the thermal noise by the second one.

According to the properties of LSC code, the direct detection technique is expressed as below

$$\sum_{i=1}^{L} C_k(i)\ C_l(i) = W\delta(k - l), \tag{11}$$

here $\delta(k)$ is the Dirac delta function.

To simplify the analysis, Gaussian approximation is used for BER calculation. The received optical signal has a power spectral density (PSD) given by [16, 22]

$$\begin{aligned} r(\nu) &= \frac{P_{sr}}{\Delta\nu}\sum_{k=1}^{N} d_k \sum_{i=1}^{L} C_k(i)\left\{u[\nu-\nu_0-\frac{\Delta\nu}{2L}(-L+2i-2)]-u[\nu-\nu_0-\frac{\Delta\nu}{2L}(-L+2i)]\right\} \\ &= \frac{P_{sr}}{\Delta\nu}\sum_{k=1}^{N} d_k \sum_{i=1}^{L} C_k(i)\, u\left[\frac{\Delta\nu}{L}\right], \end{aligned} \tag{12}$$

where P_{sr} stands for the effective power at the receiver, N stands for the number of active users, d_k is the data bit of the kth user and $u(\nu)$ is the unit step function.

$$u(\nu)=\begin{cases} 1 & ; \quad \nu \geq 0 \\ 0 & ; \quad \nu < 0 \end{cases} \tag{13}$$

From Equation 12, and during one period, the sum of power spectral density at the photo-detector of the lth receiver can be expressed as [18].

$$\int_0^{+\infty} G_d(\nu)d\nu = \int_0^{+\infty} \frac{P_{sr}}{\Delta\nu}\sum_{k=1}^{N} d_k \sum_{i=1}^{L} C_k(i)\, C_l(i)\, u\left[\frac{\Delta\nu}{L}\right] d\nu \tag{14}$$

Substituting Equations 11 and 12 in Equation 14, we obtain [18]

$$\int_0^{+\infty} G_d(\nu)d\nu = \frac{P_{sr}}{\Delta\nu}\left[W\frac{\Delta\nu}{L}\right] = \frac{P_{sr}W}{L}. \tag{15}$$

The photo-current, I, at the output of the photo-detector is given as [18]:

$$I = \Re\int_0^{+\infty} G_d(\nu)d\nu = \Re\frac{P_{sr}W}{L} \tag{16}$$

where,
$\Re$: the responsivity of the photo-detector, calculated by $\Re = \frac{\eta e}{h\nu_0}$;
η: the quantum efficiency;
h : the Planck's constant.

Substituting Equation 16 in Equation 10, the noise variance is expressed as

$$\sigma^2 = 2\frac{eB\Re P_{sr}W}{L} + 4\frac{K_B T_n B}{R_L}. \tag{17}$$

Considering an equiprobable transmission of bits "1" and "0", for each user, the average SNR is

$$SNR = \frac{I^2}{\sigma^2} = \frac{\left(\frac{\Re P_{sr}W}{L}\right)^2}{2\frac{eB\Re P_{sr}W}{L} + 4\frac{K_B T_n B}{R_L}}. \tag{18}$$

Using NRZ-OOK (nonreturn to zero – on-off keying) as modulation scheme, BER can be computed by [16, 22]

$$BER = \frac{1}{2}erfc\left(\sqrt{\frac{SNR}{8}}\right), \tag{19}$$

where $erfc$ is the complementary error function.

5. Results and discussions

A numerical comparison of the LSC code performance has been achieved with the recently proposed codes having the same correlation property ($\lambda_C = 0$), such as : the ZCC code and the MMS code. We have evaluated, by MATLAB, the BER using Equation 19, where, Table 3 recapitulates the parameters used in numerical calculations. BER and SNR are inversely related. Greater is the SNR, smaller is the BER, and hence better is the communication.

Table 3. Typical parameters used in numerical calculation.

Symbol	Parameter	Value
λ_0	Central wavelength	1550 nm
η	Photo-detector quantum efficiency	0.8
B	Electrical bandwidth	311 MHz
P_{sr}	Broadband effective power	–10 dBm
R_L	Receiver load resistor	1030 Ω
T_n	Absolute receiver noise temperature	300 K
h	Planck's constant	6.6260×10^{-34}
e	Electron charge	1.602×10^{-19}

Figure 2 illustrates the performance of the SAC-OCDMA system, at 311 MHz and transmit power of –10 dBm, versus the number of active users. It is clearly observed that the LSC code gives the best performance. The graphs show that increasing the number of users degrades the system performance. Moreover, for the LSC code the constraint of optical networks (BER of 10^{-9}) is respected in the presence of 117 active users, while MMS and ZCC codes allow only 96 and 69 active users, respectively.

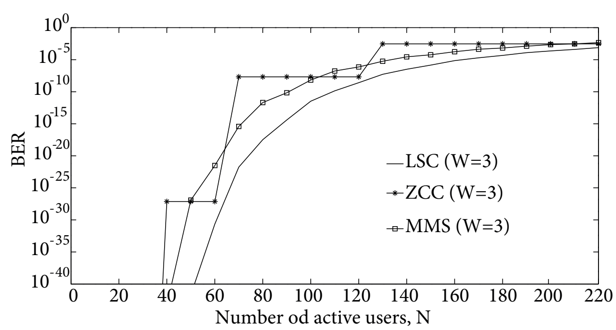

Figure 2. Performances of the LSC, MMS and ZCC codes in terms of BER versus number of active users.

Figure 3 shows the performance of 40 active users with received power of –10 dBm at various bit rates. We can notice that the LSC code presents the best performance. Usually, the increase in the signal bit rate degrades the OCDMA system performance. This is due to the fact that the high values of the bit rate induce a smaller pulse width. Hence, the influence of dispersion on the overall system becomes more important. Furthermore, it can be observed that the proposed code can be used with bit rate more than 4.6 Gbit/s while retaining a low BER (BER = 10^{-9}) and is better than the MMS (3.3 Gbit/s) and ZCC (2 Gbit/s) codes.

Figure 4 shows the relationship between the system performance and the effective power of various codes with W=3 and N=40. It can be observed that the LSC code needs (P_{sr}=-14.5 dBm) to achieve the

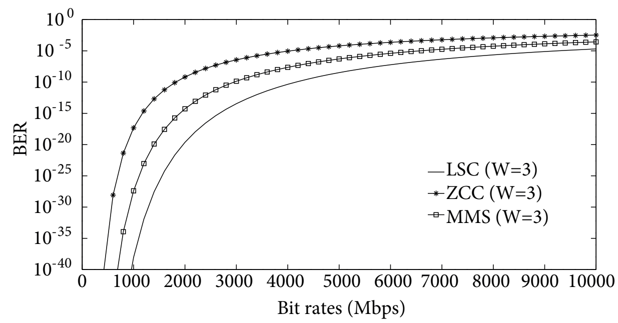

Figure 3. BER against the bit rates for various codes employing the SAC-OCDMA technique.

upper limit acceptable BER value , while the MMS and ZCC codes require (P_{sr}=-14 dBm) and (P_{sr}=-12.6 dBm), respectively. Therefore, the SAC-OCDMA system using the LSC code can benefit from a mitigation of approximately 2 dBm in the power required compared to the other codes while assuring the same performance.

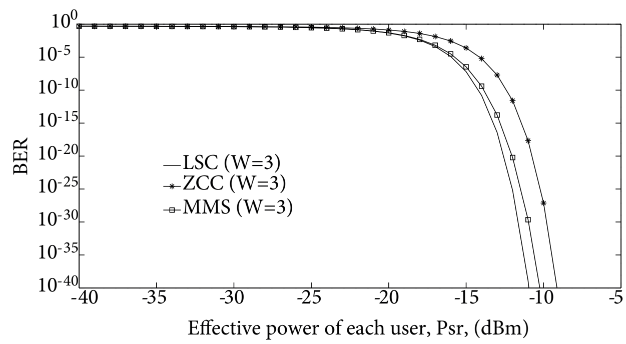

Figure 4. BER versus the effective received power from every user for various codes employing the SAC-OCDMA technique.

To analyze the performance of the LSC code in an environment as close as possible to the reality, we have used OptiSystem version 14.0. Figure 5 shows a block diagram for 6 users with spectral chip width of 0.8 nm. The tests were performed using parameters listed in Table 3 with the ITU-TG.652 standard single- mode optical fiber (SMF). We have activated and specified all the parameters according to the typical industry values, such as : the nonlinear effects, the attenuation (i.e. 0.25 dB/km) and the dispersion (i.e. 18 ps/nm km). The noises at the receivers were considered to be randomly generated 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 performances of the system were characterized in terms of BER and eye diagram.

The comparison between theoretical (equation19) and simulated values of the BER is shown in Figure 6. It should be noted that to validate the Gaussian approximation results, the simulation is tested back-to-back (i.e. in the absence of SMF between the transmitter and the receiver) for 6 active users. We can see that the two curves show a very good agreement. Thus, the simulation results validate the theoretical expression of BER.

Figure 7 shows that the LSC code gives a BER value of 10^{-42} in a back-to-back case. And Figure 8 illustrates a degradation of the system performance for a distance of 40 km, this is interpreted by an increase in the BER to 10^{-27}. It is found that this value is better than that obtained by several other existing SAC-OCDMA codes such as ZCC code and MMS code as latterly tackled by the authors [17, 23].

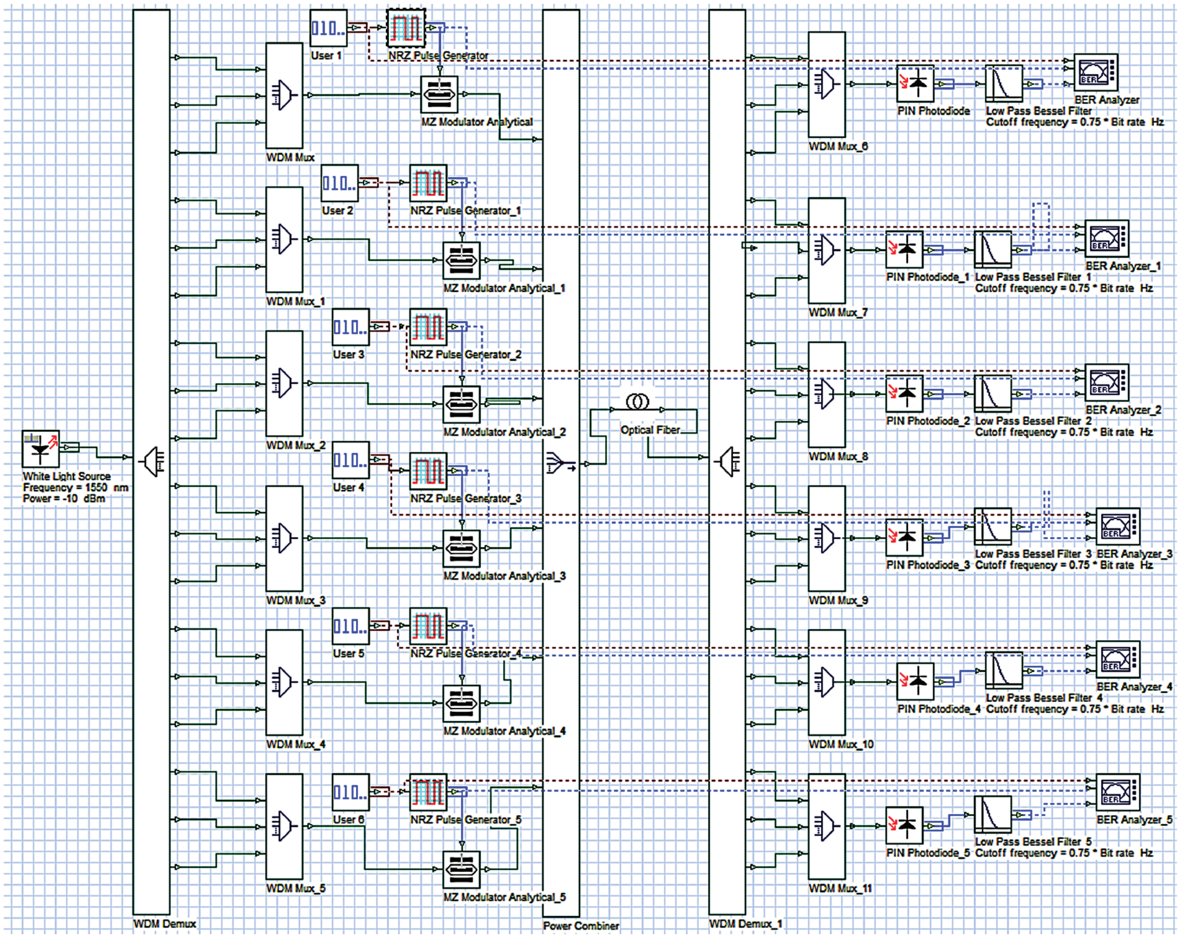

Figure 5. LSC code schematic block diagram for 6 users.

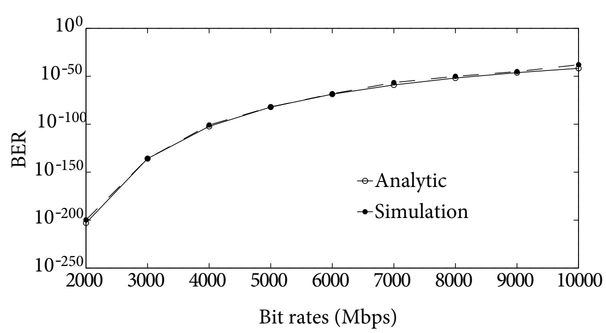

Figure 6. A comparison between theoretical and simulation BER values of the LSC code.

6. Conclusion

In this paper, a new family of codes with a zero cross-correlation property, called Latin square code (LSC), has been successfully designed and simulated for SAC-OCDMA system. The performances of this code have been analyzed and compared to the other available codes having the same correlation property (ZCC, MMS). The

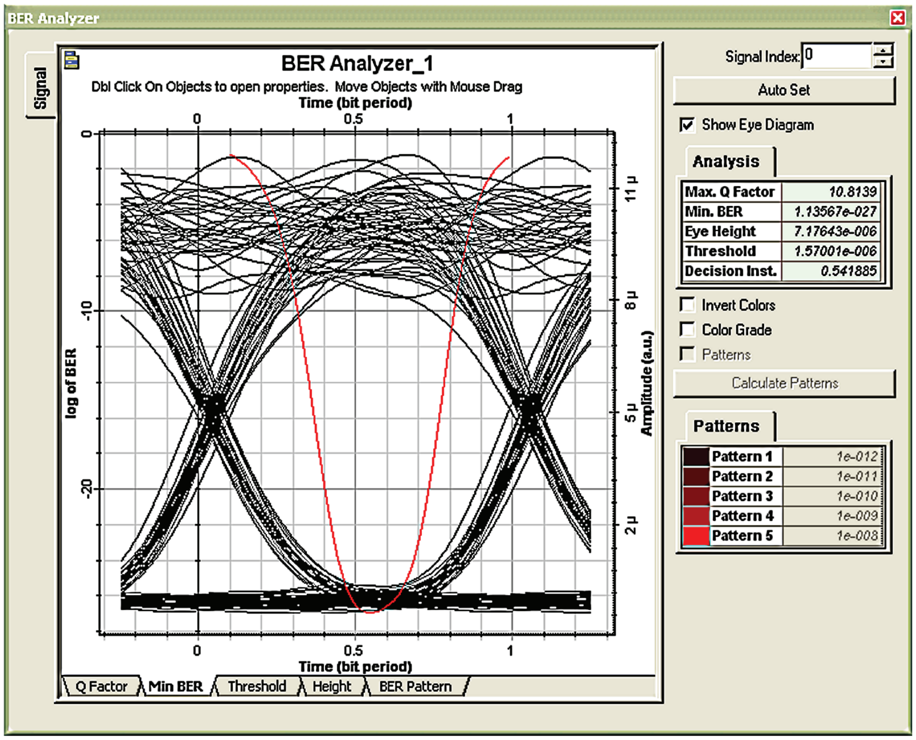

Figure 7. Eye diagram of the SAC-OCDMA system using the LSC code in back to back link for N = 10 and W = 3.

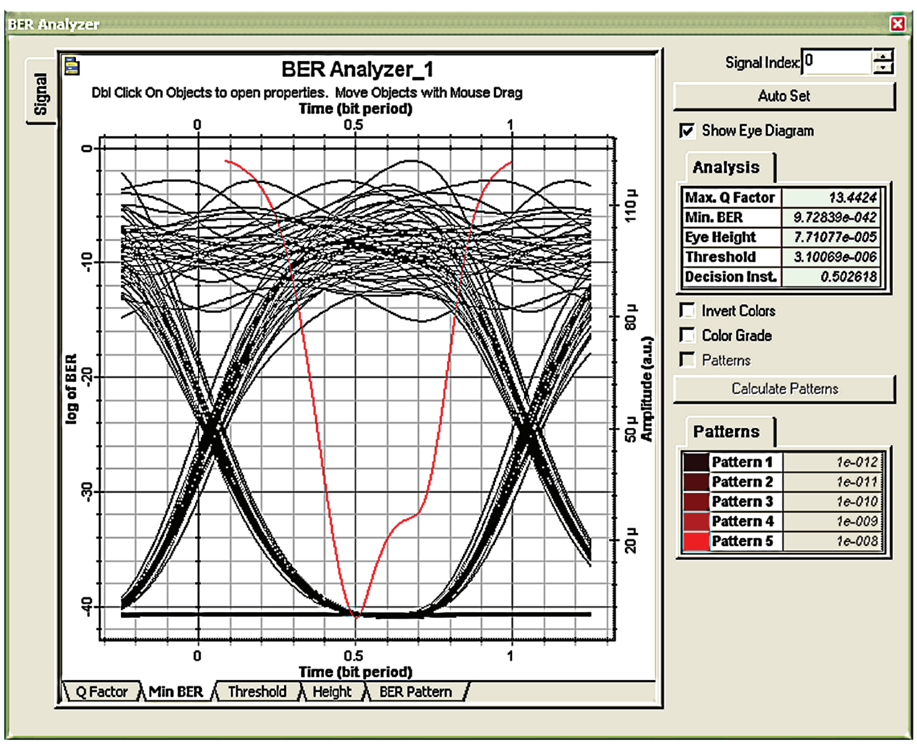

Figure 8. Eye diagram indicating performance of 10 users with weight three using LSC code at 40 km

evaluation of the proposed LSC code has been based on the theoretical calculation and the simulation of the SAC-OCDMA system. For this, the direct detection technique has been used in the presence of the thermal and shot noises.

The LSC code offers several advantages, in comparison with the other existing codes in the literature, such as: simplicity in code construction, suppleness in selecting the code parameters, short code length, minimum BER, and zero cross-correlation which eliminates the MAI and PIIN.

Numerical results have been shown that using the proposed LSC code, the SAC-OCDMA system supports 117 and 40 active users at 622 Mbit/s and 4.6 Gbit/s, respectively. It respects the optical transmission constraint, BER 10-9, using a transmission source with an effective power lower than -14.5 dBm. It can also used over long distances with an acceptable BER level. Thus, the advantages of this code could make it a code for future generation optical networks.

Finally, the proposed work can be extended by testing the LSC code for the use in wireless optical systems. Moreover, a 2D-LSC coding algorithm can be proposed by adding a spatial encoding technique as a second dimension to the LSC code.

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