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# A new family of 2D-wavelength-time codes for OCDMA system with direct detection

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## Abstract

A new family of two dimensional wavelength-time codes is proposed in this paper. Based on one-dimensional ZCC, it allows a higher cardinality without increasing the code length, while conserving the same correlation properties. Thus, the direct detection at the receiver can be used, thereby simplifying the architecture of wavelength-time OCDMA scheme. The performance of the system was evaluated by referring to the Q factor, the BER and the eye pattern diagrams.

## Keywords:

Wavelength-time  
2D-OCDMA  
ZCC  
BER

## 1. Introduction

Spectral-amplitude coding OCDMA (SAC-OCDMA) also known as Frequency Encoded-Code Division Multiple Access (FE-OCDMA), is a multiplexing technique adapted from radiofrequency CDMA systems [1–8]. It has proved to be very promising as by employing appropriate code families (such as PC [1], OOC [2], ZCC [3–7], PMQCC [8] and GMPC [9]) and detection scheme (balanced [8], [9] or direct [5]). It can considerably reduce the negative effect caused by the multi access interferences (MAI) and the receiver shot, dark current and thermal noise sources. However, there are some disadvantages in 1D-OCDMA, such as large bandwidth consumption and limited allowed number of users. 2D-OCDMA codes have been proposed to solve this constraint. One effective way to generate 2-D optical codes is to apply the existing 1-D coding technique in a combined time spreading and wavelength-hopping scheme [10–17]. In the 2-D coding approach, each chip is assigned to a different wavelength and placed across the bit period [10]. The 2D-OCDMA codes afford more flexibility and better performances than 1D-OCDMA codes [15].

This paper is organized as follow. In section 2 we review the ZCC code elaboration [3]. Section 3 is devoted to the proposed 2D-ZCC code's construction. In section 4 the network simulation of a four users system using Optisystem 9.0 [18] will be presented, followed by the result's discussion given in Section 5.

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**Table 1**  
ZCC codes generated with code length  $L = 13$ , weight  $w = 3$  and  $N = 4$ .

	Positions of chips "1"			Codes
$C_1$	1	3	9	1010000010000
$C_2$	2	6	5	0100110000000
$C_3$	4	12	10	0001000001010
$C_4$	8	11	7	0000001100100

## 2. One dimensional ZCC codes

Inspired by MDW (Modified Double Weight) codes [19], ZCC codes were designed to solve the MAI problem (resulting from the simultaneous transmission of all users) and suppress the effect of the phase induced intensity noise (PIIN) which are the major cause of the signal to noise ratio limitation.

An  $(L, w)$ -ZCC code, with length  $L > 1$  and weight  $w \geq 1$ , is a code family satisfying the following property [3–6]:

$$\sum_{i=0}^{L-1} x(i) \times y(i) = 0 \quad (1)$$

For all pairs of distinct codes  $x()$ ,  $y()$  in  $(L, w)$ -ZCC code.

In order to increase the number of users  $N$  (number of users supported by the system), different methods exist [3–6]. Authors in [3] propose to use a method based on BIBD (Balanced Incomplete Block Design) to generate ZCC codes, solving the codes' length problem and avoiding the use narrow band filters.

It is important to note that in this construction method, the number of users  $N$  is determined based on equation (2) as follows [3]:

$$(N - 1) + (w - 1) \times N \leq L - 2 \quad (2)$$

This implies

$$N \leq \left\lfloor \frac{L - 1}{w} \right\rfloor \quad (3)$$

Where  $[x]$  denotes the integer par of  $x$ .

For example the ZCC codes generated with code length  $L = 13$ , weight  $w = 3$  and  $N = 4$  are given in Table 1. (The detailed construction method is explained in [3]).

## 3. Two dimensional approach

Wavelength-Time (W-T) codes are generated either by using mathematical approach [11], [12] or by extension of existing one dimensional code [13–16]. Mendez et al. [11] generated two-dimensional codes or matrices from pseudo-orthogonal (PSO) sequences, by means of simple quasi-graphical operations, and obtained 32 matrices with a cross-correlation  $\lambda_c = 1$ , these codes were also used in [12] to simulate a 2D-OCDMA W/T system. Heo et al. [14] proposed W-T codes based on 1D BCDD (Balanced Code for Differential Detection) codes implemented in OCDMA with balanced detection. This scheme allows a large number of simultaneous users. These authors cited the advantage of this code as being the code size (the number of chips  $\times$  the number of wavelengths). Nasaruddine et al. [13] developed a code reconfiguration design for two-dimensional OCDMA system to enhance security. The obtained 2-D OCDMA codes are constructed by using quasi-groups (QGs) and one-dimensional (1-D) optical orthogonal codes (OOCs), called QG/OOCs, the cross correlation of these codes is  $\lambda_c = 1$  and their cardinality depends on the weight and the number of available wavelengths. Chang et al. [15] described a 2D-OCDMA scheme with arrayed wavelength guide (AWG) used to generate M-sequence code pattern in a cyclic way to set up W-T codes with a cross-correlation  $\lambda_c = G \times w$ , where  $G$  denote the number of wavelengths.

In the proposed work 2D ZCC/ZCC codes are obtained, based on the construction idea of 2-D PC/PC codes [17], by using one dimensional ZCC codes [3] for both wavelength-hopping and time-spreading. The Advantages of proposed case are

- Significant increase in the number of users maintaining the same weight;
- Length code unchanged which involves the use broadband filters (cheaper than narrowband filters);
- Maintain of the cross-correlation property of the one dimensional ZCC codes.

### a. Construction

Let's:

$$\begin{cases} C_{i,k} = \alpha^{(i+kN)} \text{mod} L \\ H_{j,k} = \alpha^{(j+kN)} \text{mod} L \end{cases}$$

Where  $C_{i,k}$  is used as time spreading (it determine the positions of the wavelengths) and  $H_{j,k}$  is used as wavelength-hopping (it establish the wavelength's index) and  $\alpha$  is said to be a primitive element of  $L$  [3].

With

$$0 \leq i \leq N - 1$$

$$0 \leq j \leq N - 1$$

$$0 \leq k \leq w - 1$$

Example for  $L = 13$ ,  $\alpha = 2$ ,  $i = 0$ ,  $j = 1$ ,  $w = 3$  and  $N = 4$

$$C_{0,k} = 2^{(4k)} \text{mod} 13$$

$$= \begin{cases} 1, k = 0 \\ 3, k = 1 \\ 9, k = 2 \end{cases}$$

$$H_{1,k} = 2^{(1+4k)} \text{mod} 13$$

$$= \begin{cases} 2, k = 0 \\ 6, k = 1 \\ 5, k = 2 \end{cases}$$

We simplify the notations by removing index k, therefore the obtained code word in this case is

$$C_0H_1 [\lambda_2 \ 0 \ \lambda_6 \ 0 \ 0 \ 0 \ 0 \ 0 \ \lambda_5 \ 0 \ 0 \ 0 \ 0]$$

The 2D ZCC/ZCC (W-T) codes matrices are obtained by associating the rows with wavelengths (or frequency) and the columns with time-slots [10].

Example the code matrix of  $C_0H_1$  is represented as follow:

$$\begin{matrix} \lambda_{13} \\ \lambda_{12} \\ \lambda_{11} \\ \lambda_{10} \\ \lambda_9 \\ \lambda_8 \\ \lambda_7 \\ \lambda_6 \\ \lambda_5 \\ \lambda_4 \\ \lambda_3 \\ \lambda_2 \\ \lambda_1 \end{matrix} \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_7 & t_8 & t_9 & t_{10} & t_{11} & t_{12} & t_{13} \end{pmatrix}$$

Two codewords can be differentiated with either the wavelength hopping or the time spreading, like shown in Figs. 1 and 2. For example, see Fig. 1, it is clear that the codes  $C_0H_0$  and  $C_1H_0$  share the same spectral signature ( $\lambda_1$ ,  $\lambda_3$ ,  $\lambda_9$ ) but transmit them at different time slots. We also notice that if two codes uses the same time slots like  $C_0H_0$  and  $C_0H_2$  they send different wavelengths, thus maintaining a zero cross correlation.

b. Correlation properties

Autocorrelation of a W-T code  $x(t)$  is defined as [10]:

$$Z_{x,x}(l) = \sum_{m=1}^R \left( \sum_{n=1}^L x_{m,n} x_{m,(n+l) \text{mod} L} \right) \quad (4)$$

With:

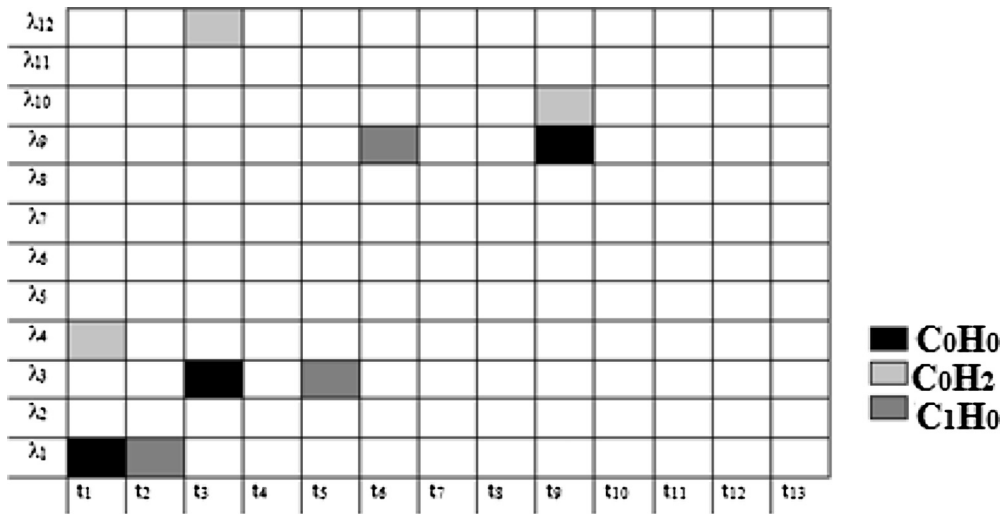


Fig. 1. Code's illustration  $C_0H_0$ ,  $C_0H_2$  and  $C_1H_0$ .

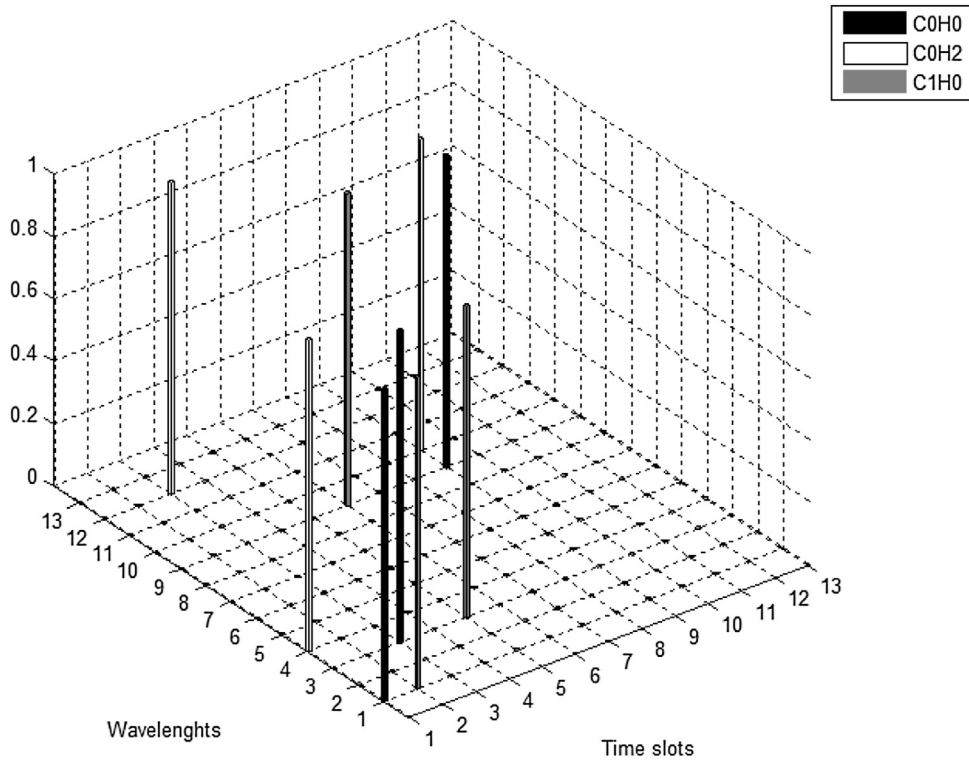


Fig. 2. 3D Code's illustration  $C_0H_0$ ,  $C_0H_2$  and  $C_1H_0$ .

$L$  is number of columns;  
 $R$  is the number of rows;

$$0 \leq l \leq L$$

The obtained codes satisfies

$$\lambda_a = Z_{x,x}(l) = \begin{cases} w, & l = 0 \\ 0, & 1 \leq l \leq L \end{cases}$$

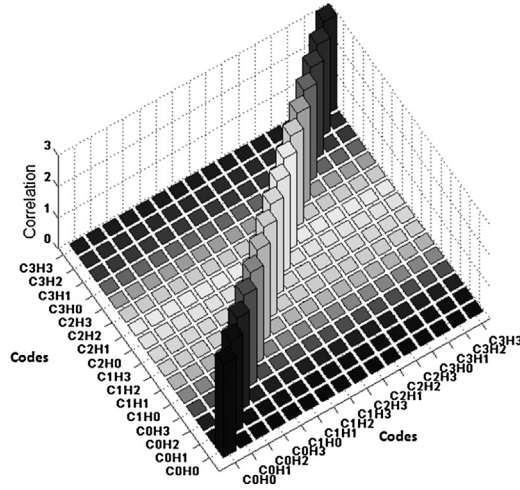


Fig. 3. Correlation results  $l = 0$ .

**Table 2**

Comparison of cardinality with existing codes.

Code	Number of users supported
PC/PC [17]	$N(N - 1)$
OCFHC/OCC[20]	$\frac{L(N_{\text{OOC}}-1)}{w(w-1)}$
2D-EDW [21]	$N$
Proposed ZCC/ZCC	$N^2$

$N_{\text{OOC}}$  is the number of users of 1D-OOC codes.

The cross-correlation between two W-T codes  $x(t)$  and  $y(t)$  is defined as [10]:

$$Z_{x,y}(l) = \sum_{m=1}^R \left( \sum_{n=1}^L x_{m,n} y_{m,(n+l) \bmod L} \right) \quad (5)$$

In our case

$$\lambda_c = Z_{x,y}(l) \begin{cases} = 0, & l = 0 \\ \leq w - 1, & 1 \leq l \leq L \end{cases}$$

Both auto and cross-correlation for all the obtained codes (16 codes) from the presented case are shown in Fig. 3.

Table 2 compares the cardinality of 2D ZCC/ZCC codes with other existing two dimensional codes where the number of users depends on the 1D cardinality.

#### 4. Simulation setup

The performance analysis of 2D-ZCC/ZCC codes was simulated by using the software Optisystem version 9.0. Each code chip width is 100 GHz starting from 1550 nm. A delay time “ $t$ ” was introduced between the different wavelengths of each user’s code. The simulation setup is shown in Fig. 4.

##### a. Emission part

Using an array of continuous wave (CW) lasers, we generate the required group of  $w$  wavelengths for each user. This source power was limited to a time  $\tau$  of the bit period with a repetition rate of  $t_b$  ( $t_b$  is the bit period ( $1/\text{Bit rate}$ ) and  $\tau = \frac{t_b}{S}$ ,  $S$  is the number of time slots). It is then modulated by an input data, in an optical modulator, using an on-off keying mode. The optical pulse corresponding to data bit “1” is divided into  $w$  optical pulses [6]. Each one is delayed by [10]:

$$t_j = j \times \tau \quad (6)$$

With  $j$  is the chip’s position ( $j = 1, \dots, S-1$ ).

The W-T encoder is represented in Fig. 5, the code  $C_0H_0$  is taken as an example.

##### b. Reception part

Each wavelength is firstly detected then delayed through delay lines. The time delay at the reception  $t'_j$  is calculated as follow:

$$t'_j = (S - 1 - j) \quad (7)$$

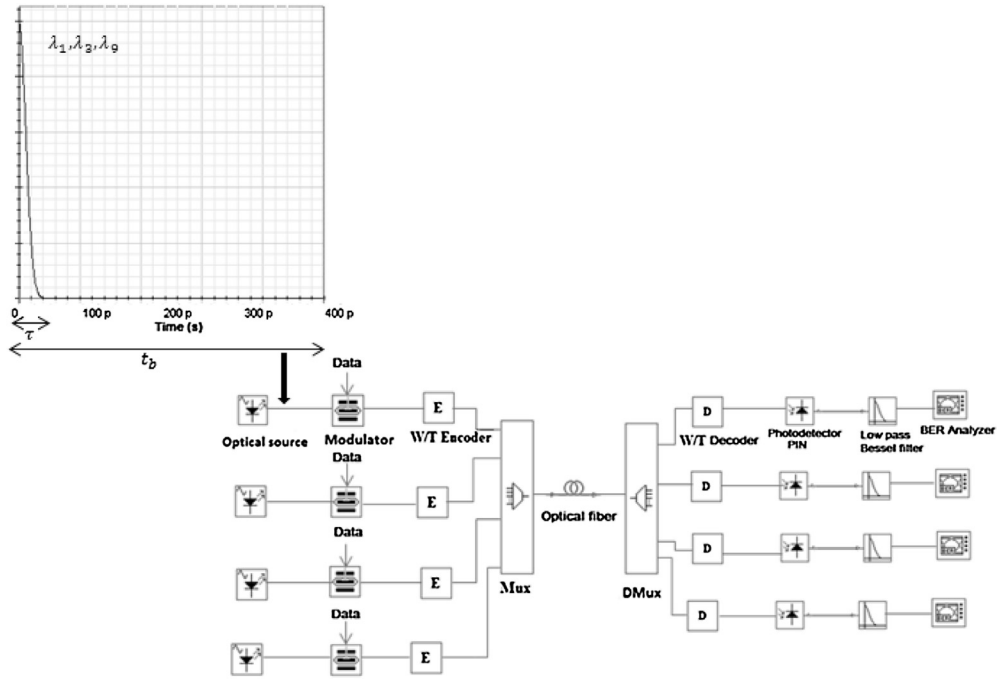


Fig. 4. Simulation setup.

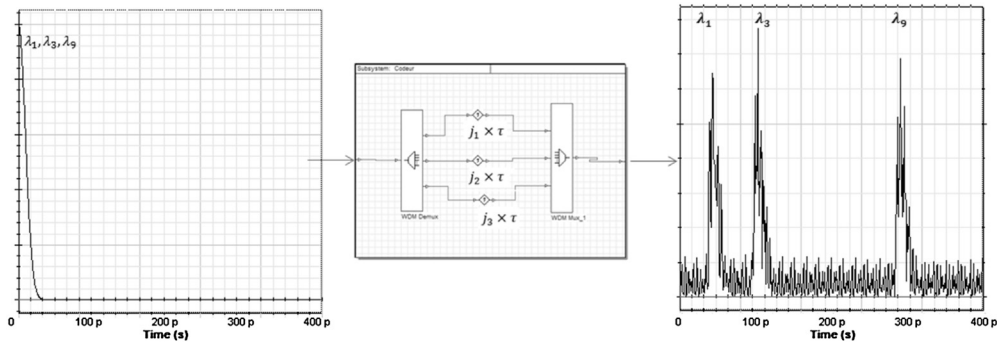


Fig. 5. 2D Encoder.

Detection is made by using optical filters Bessel. The decoder scheme is shown in Fig. 6.

### c. Simulation parameters

Each chip has a spectral width of 100 GHz (0.8 nm). The data bit rate equals 2.5 Gbits/s for a 30 km ITU-G652 standard single mode optical fiber [2]. To simulate the real environment as accurately as possible, the following classic industry values are considered [10], [11]: Attenuation = 0.2 dB/km; Dispersion = 18 ps/nm/km; Dark current of the PD's = 5 nA; Thermal noise =  $1.8 \times 10^{-23}$  W/Hz.

## 5. Performance analysis

The performance of the system is characterized by referring to the Q factor, the BER and the eye pattern diagram. The Q factor curve and the eye diagram of one of the users when all 4 users are simultaneously active, using  $C_0H_0$ ,  $C_0H_1$ ,  $C_0H_2$  and  $C_0H_3$  codes, are shown in Fig. 7. According to it, a maximum Q factor value of 8.31 can be obtained. It corresponds to a minimum BER value of  $4.52 \times 10^{-17}$ . The eye is wide open which means that the system is resistant to noise. All the calculations were made without the use of any dispersion compensating fiber (DCF). As shown in [22], the simulation results confirms that 2D-OCDMA systems can perform under a higher bit rate (2.5 Gbits/s) than 1D-OCDMA (622 Mbits/s) [5,6].

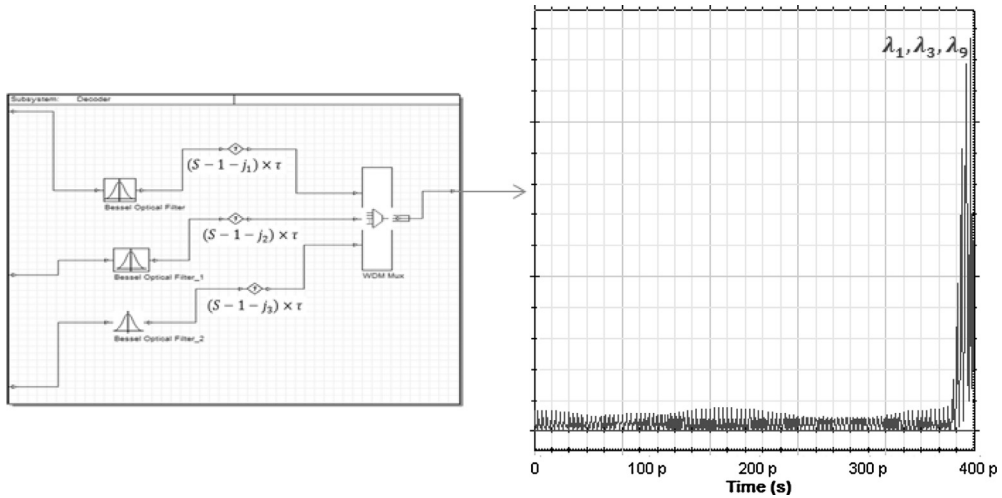


Fig. 6. 2D decoder of the code  $C_0H_0$ .

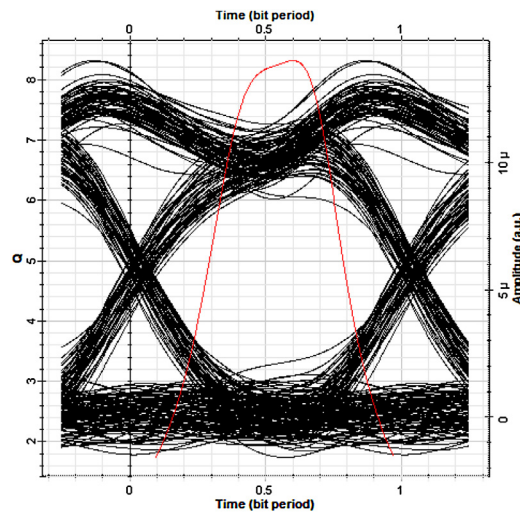


Fig. 7. Q factor and eye diagram.

## 6. Conclusion

In this paper, we have proposed an easy construction of two dimensional W-T codes, based on the 1D-ZCC ones, maintaining the code's length and assuring a higher cardinality. It has been shown that the cardinality of the proposed 2D ZCC/ZCC code is higher than that existing codes and namely  $N$  times higher than that of the 2D -PC/PC codes.

The conservation of the zero cross correlation property allowed us to suppress phase induced intensity noise (PIIN) effect and to use a simple detection system, avoiding thus the balanced detection.

The performance of the system was simulated by using Optisystem 9.0. The simulation experiment showed successful implementation of the 2D-OCDMA scheme since the sufficient system performances ( $BER \leq 10^{-9}$ ,  $Q \geq 6$ ) are respected.

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