Simulation and Analysis of Optimum Golomb Ruler based 2D Codes for OCDMA System

Dr. Gurjit Kaur
Department of ECE
Gautam Buddha University, Greater Noida,
U. P., India

Aarti Bhardwaj
Department of ECE
Gautam Buddha University, Greater Noida,
U. P., India

Rajesh Yadav
Department of ECE
Gautam Buddha University, Greater Noida,
U. P., India

Manu Gangwar
Department of ECE
Gautam Buddha University, Greater Noida,
U. P., India

Disha Srivastava
Department of ECE,
Gautam Buddha University, Greater Noida,
U. P., India

Nidhi
Department of ECE,
Gautam Buddha University, Greater Noida,
U. P., India

***Abstract*—The need for high speed communications networks has led the research communities and industry to develop reliable, scalable transatlantic and transpacific fiber-optic communication links. In this paper the optimum Golomb ruler based 2D OCDMA codes has been demonstrated. An OCDMA system based on the discussed 2D codes is designed and simulated on Optisystem. The encoder and decoder structure of OCDMA system have been designed using filter and time delays. Further the performance is analysed for various parameter such as bit rate, number of users, BER (Bit Error Rate), quality factor, eye diagram and signal diagram. The system is analyzed for up to 18 users at 1 Gbps and 1.25 Gbps bit rate.**

Keywords—OCDMA System; 2D Codes; OOC; Golomb Ruler; BER; Eye Diagram; MAI

I. Introduction

In Local Area Networks (LANs), since the traffic is bursty, it demands high speed and large capacity communication network. The optical fiber addresses these requirements because the bandwidth of optical fiber is enormous and it can provide higher carrier frequency and therefore greater information carrying capacity of the communication and higher transmission bandwidth for the communication [1]. There are various multiple access techniques [2] which are being used to accommodate the large number of users such as Optical Code Division Multiple Access (OCDMA). The OCDMA system plays an essential role in long haul and high speed communication where users share the same transmission media [3] as shown in Figure 1.

In OCDMA each user is assigned a unique signature code which is modulated by the data of the corresponding user. The signal from all the users is combined on a single optical fiber, which is broadcasted to each user in the network. Single-user decoding is achieved by correlating the aggregate signal and the signature sequence of the desired user. If the output of the decoder is in autocorrelation then the receiver can detect the signal sent to it. On the other hand, if the decoder is in cross correlation then the receiver cannot receive the signal. For OCDMA systems, optical codes should have maximum autocorrelation and minimum cross correlation property.

As the number of user increases the Multiple Access Interference (MAI) also increases and this is the main cause of performance degradation in OCDMA network. So cross correlation is needed to be kept less for maintaining probability of error low. Many codes have been proposed for the OCDMA system. Mendez et al. presented the one dimensional optical orthogonal code [4].

In one dimensional (1-D) codes, on increasing the number of users, the length of the codes also increases. And hence, the bit rate decreases for a given chip width [5]. To overcome this problem of 1-D codes in OCDMA, two dimensional (2-D) codes have been proposed such as Time-Space (T/S) and Wavelength-Time (W/T).

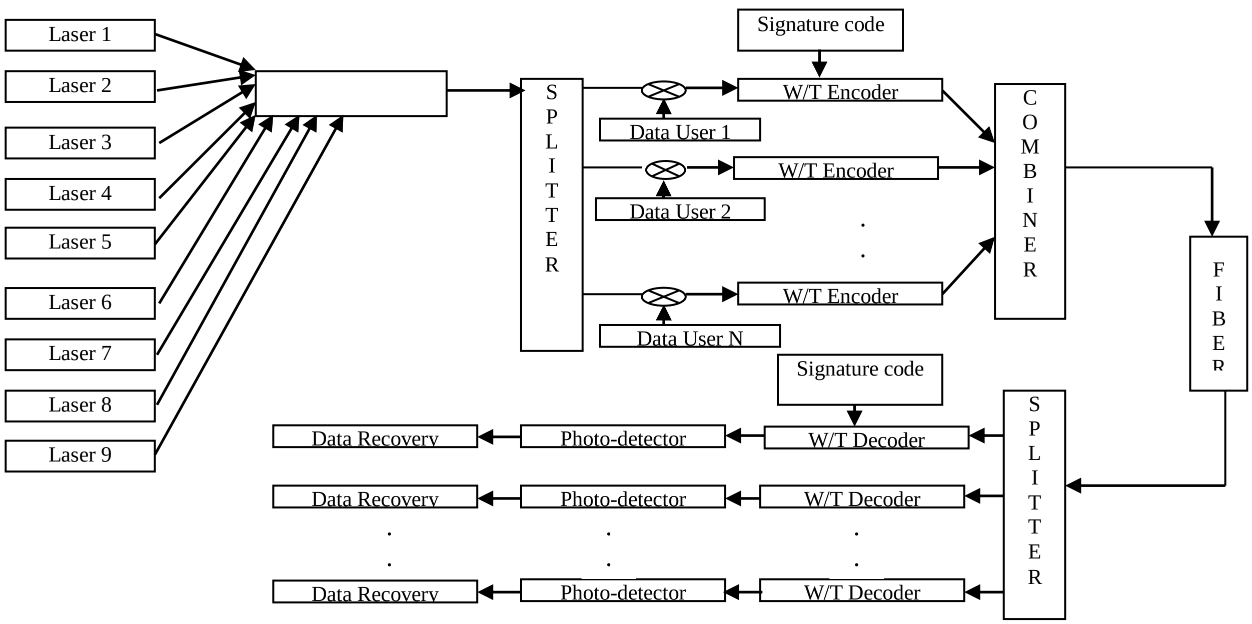


Fig. 1. OCDMA system Block Diagram

Heo have proposed the construction of 2-D wavelength-time codes by hybridization of the prime codes and the pseudo-random noise codes using differential detection with on-off keying [6]. Yeon have designed modified pseudo-random noise codes for W/T spreading with two sequences having different lengths [7]. Wan and Hu have constructed hybrid codes by concatenating the prime codes and optical orthogonal codes[8]. Mendez construct 2-D codes from 1-D Golomb rulers to increase the number of code set size [9]. In 2D optical codes, the length of the codes reduces and hence improves the BER performance. Large numbers of researchers are working on the design of 2D codes for OCDMA system [9 - 10]. In this paper, the design of Optical Orthogonal Codes (OOC) using optimum Golomb rulers has been demonstrated and the OCDMA system performance on Optisystem tool has been analyzed.

The rest of paper is organized as follows: Section II discusses the OCDMA coding theory that gives an insight of the optical codes for optical CDMA communication system. The mathematical modeling of proposed 2D optical code is described. Section III presents a concise introduction to optical OCDMA systems for simulation. Section IV discusses the result of the proposed optical prime codes and its performance estimation in terms of the autocorrelation and cross-correlation function. In section V the current findings along with the future directions are concluded. The paper ends with the references studied and cited in the paper.

II. Optical Coding Theory

A. Construction of codes

The W/T code can be represented as matrices with wavelength and time as axis. This matrix is known as Pseudo Orthogonal (PSO) matrix code. Total wavelength is divided into n different channels and total time is divided into m time slots. These PSO matrix codes are constructed with the help of spanning ruler or optimum Golomb ruler [11].

N-mark Golomb ruler is a set of n distinct non negative integers ($a_1, a_2, a_3, \ldots a_n$) called "marks" such that the positive differences $|a_i - a_j|$ computed over all possible pairs of different integers i, j = 1,2,3....n with $i \neq j$, are distinct.

A perfect Golomb ruler of order (mark) 4 and length 6 is shown in Figure 2. It is not possible to have another type of perfect ruler. So this ruler is Optimum Golomb ruler in which the distance between the two points is unique.The optimum Golomb ruler g(1, 7) of weight 7, length 26 and cardinality (number of user) 1 is shown in Figure 3. Figure 4 represents the construction of 4 code matrices M1...M4 from shifted version of Golomb ruler g (1,7) with filler zeros (shown) that increases the code dimension.

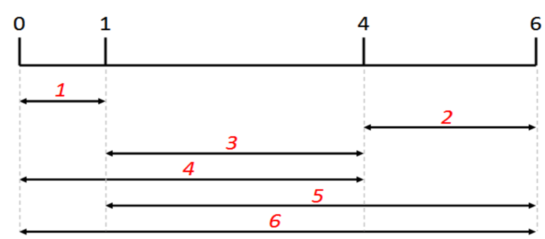


Fig. 2. Golomb ruler of order 4

The headings of table in Figure 4(a) define the column and row to which the table entries should be transposed. These matrices can be converted into 2D W/T codes by taking row as i^{th} wavelength and column as j^{th} time slot as shown in Figure 4(b). For example for matrix M4, the code will be $\{\lambda_4:\lambda_2:\_:\lambda_2:\lambda_4:\_:\lambda_1:\lambda_1\}$ which signifies fourth wavelength in first time slot, second wavelength in second time slot, second wavelength in fourth time slot, fourth wavelength in fifth time slot, first wavelength in seventh and eighth time slot.

1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1

Fig. 3. Optimum Golomb ruler g(1,7) of weight 7, length 26 and cardinality 1

	Column1				Column2				Column3				Column4				Column5				Column6				Column7				Column8			
M	**R1**	**R2**	**R3**	**R4**	**R1**	**R2**	**R3**	**R4**	**R1**	**R2**	**R3**	**R4**	**R1**	**R2**	**R3**	**R4**	**R1**	**R2**	**R3**	**R4**	**R1**	**R2**	**R3**	**R4**	**R1**	**R2**	**R3**	**R4**	**R1**	**R2**	**R3**	**R4**
1	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
2	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0
3	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0
4	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0

Fig. 4. (a): Construction of code matrices

M1=

	C1	C2	C3	C4	C5	C6	C7	C8
r1	1	0	0	0	1	0	0	0
r2	0	0	0	0	0	1	1	0
r3	1	0	1	0	0	0	0	0
r4	1	0	0	0	0	0	0	0

M2 =

	C1	C2	C3	C4	C5	C6	C7	C8
r1	0	0	0	0	0	0	0	0
r2	1	0	0	0	1	0	0	0
r3	0	0	0	0	0	1	1	0
r4	1	0	1	0	0	0	0	0

M3=

	C1	C2	C3	C4	C5	C6	C7	C8
r1	0	1	1	0	1	0	0	0
r2	0	0	0	0	0	0	0	0
r3	1	0	0	0	0	1	0	0
r4	0	0	0	0	0	0	1	0

M4 =

	C1	C2	C3	C4	C5	C6	C7	C8
r1	0	0	0	0	0	0	1	1
r2	0	1	0	1	0	0	0	0
r3	0	0	0	0	0	0	0	0
r4	1	0	0	0	1	0	0	0

Fig. 4. (b): Construction of code matrices

Now the concept of folded optimum Golomb ruler has been expended by using more than one optimum Golomb ruler as shown in Figure 5 and design a matrix with eight wavelength (8 rows) and four time slots (4 columns) that can produce (8×4) = 32 Pseudo Orthogonal (PSO) codes as represented in Figure 6. It should be noted that the cardinality goes from 4 to 32.

1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0

$g_1(4,4)$

1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1

$g_2(4,4)$

1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0

$g_3(4,4)$

1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0

$g_4(4,4)$

Fig. 5. Optimum Golomb rulers of weight 4, length 25 and cardinality 4

	Column 1								Column 2								Column 3								Column 4							
M	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0

Fig. 6. (a): Construction of code matrix for 8 users

$$M1=\begin{bmatrix}1\,0\,0\,0\\0\,1\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,1\,0\\0\,1\,0\,0\\0\,0\,0\,0\end{bmatrix}\quad M2=\begin{bmatrix}0\,0\,0\,0\\1\,0\,0\,0\\0\,1\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,1\,0\\0\,1\,0\,0\end{bmatrix}\quad M3=\begin{bmatrix}0\,0\,1\,0\\0\,0\,0\,0\\1\,0\,0\,0\\0\,1\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,1\,0\end{bmatrix}\quad M4=\begin{bmatrix}0\,0\,0\,1\\0\,0\,1\,0\\0\,0\,0\,0\\1\,0\,0\,0\\0\,1\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\end{bmatrix}\quad M5=\begin{bmatrix}0\,0\,0\,0\\0\,0\,0\,1\\0\,0\,1\,0\\0\,0\,0\,0\\1\,0\,0\,0\\0\,1\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\end{bmatrix}\quad M6=\begin{bmatrix}0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,1\\0\,0\,1\,0\\0\,0\,0\,1\\1\,0\,0\,0\\0\,1\,0\,0\\0\,0\,0\,0\end{bmatrix}\quad M7=\begin{bmatrix}0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,1\\0\,0\,1\,0\\0\,0\,0\,0\\1\,0\,0\,0\\0\,1\,0\,0\end{bmatrix}\quad M8=\begin{bmatrix}0\,0\,1\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,0\\0\,0\,0\,1\\0\,0\,1\,0\\0\,0\,0\,0\\1\,0\,0\,0\end{bmatrix}$$

Fig. 6. (b): Codes for 8 users

From Figure 6(b), the code for matrix M1 will be $\{\boldsymbol{\lambda}_1 : (\boldsymbol{\lambda}_2, \boldsymbol{\lambda}_7) : \boldsymbol{\lambda}_6\}$ and the code for matrix M2 will be $\{\boldsymbol{\lambda}_2 : (_3, \boldsymbol{\lambda}_8) : \boldsymbol{\lambda}_7\}$. Similarly the code for matrices M3....M32 can be constructed.

The code dimension can be determine as: if r is the number of rows, c is the number of columns and L is the length of Golomb ruler then shifting of Golomb ruler is shown in figure 6(a). The dimension of matrix is r×c and there are r×c-L possible shifts. It shows that the number of shifts permitted is r×c. So, the following equation should hold true to assure that matrix code set size m is equal to the number of rows in the matrices [12].

r×c-L $\geq$ r-1

Here, the length of Golomb ruler is 25, r=8 (wavelengths) and c=4 (time slots). So the possible shifts are equal to 8×4-25=7.

B. Probability of error in W/T codes

One dimensional codes spread either in time or frequency. Several types of 1-D codes are OOC, ZCC, Walsh code and Hadamard code. These codes can be characterized by N (L_t, W, λ_a, λ_c). Where

- N is the number of code
- L_t is the temporal length of the code
- W is the weight of the code (number of ones in the code)
- λa is out of phase autocorrelation peak
- λc is Cross correlation peak

The autocorrelation of one dimensional code x(t) is defined as

$$Z_{x,x}(l) = \sum_{n=0}^{L_T-1} x_n \, x_{(n+l) mod L_T} \quad (1)$$

$Z_{x,x}(l)$ satisfies

$$Z_{x,x}(l) \begin{cases} = W & if\ l = 0 \\ \leq \lambda_a & if\ 1 \leq l \leq L_T - 1 \end{cases}$$

The cross correlation of one dimensional code x(t) and y(t) is defined as

$$Z_{x,y}(l) = \sum_{n=0}^{L_T-1} x_n \, y_{(n+l) mod L_T} \quad (2)$$

$Z_{x,y}(l)$ satisfies

$$Z_{x,y}(l) \ \leq \boldsymbol{\lambda_c} \quad if\ 0 \leq l \leq L_T - 1$$

The autocorrelation of 2-dimensional codes x(t) is defined as

$$Z_{x,x}(l) = \sum_{m=0}^{R-1} \left(\sum_{n=0}^{L_T-1} x_{m,n} \, x_{m,(n+l) mod L_T} \right) \quad (3)$$

$Z_{x,x}(l)$ satisfies

$$Z_{x,x}(l) \begin{cases} = W & if\ l = 0 \\ \leq \lambda_a & if\ 1 \leq l \leq L_T - 1 \end{cases}$$

The cross correlation of 2-dimensional codes x(t) and y(t) is defined as

$$Z_{x,y}(l) = \sum_{m=0}^{R-1} \left(\sum_{n=0}^{L_T-1} x_{m,n} \, y_{m,(n+l) mod L_T} \right) \quad (4)$$

$Z_{x,y}(l)$ satisfies

$$Z_{x,y}(l) \ \leq \lambda_c \quad if\ 0 \leq l \leq L_T - 1$$

The probability of error/bit P_e is given by

$$P_e = \frac{1}{2} \sum_{i=Th}^{N-1} \binom{N-1}{i} \left(\frac{W^2}{2L_T}\right)^i \left(1 - \frac{W^2}{2L_T}\right)^{N-1-i} \quad (5)$$

III. SYSTEM SIMULATION

The OCDMA system based on the optical codes is simulated by a commercial fiber optic simulation tool. The transmitter and receiver section of the OCDMA system based on W/T code is shown in Figure 7 and Figure 9 with their corresponding parameters in Table 1 and Table 2. In transmitter section, CW (Continuous Wave) laser is used as an optical source, Pseudo random Bit Sequence (PRBS) generator is used to generate random data and Mach-Zehnder Modulator to modulate the carrier signal generated by PRBS generator. Eight different wavelengths range from 1549.2 nm to 1554.8 nm with wavelength spacing 0.8 nm are multiplexed by WDM (Wavelength Division Multiplexer) from the laser array.

The modulated signal of each user is assigned a unique code by encoder which is shown in Figure 8. It consists of optical filters, time delays, splitter and combiner, the splitter splits the carrier signal and optical filters selects four specific wavelengths from the carrier signal to produce the encoded bit sequence. The time delay in the encoder places the selected pulses of specific wavelengths in appropriate time slot and combiner combines these four pulses to construct the encoded signal.

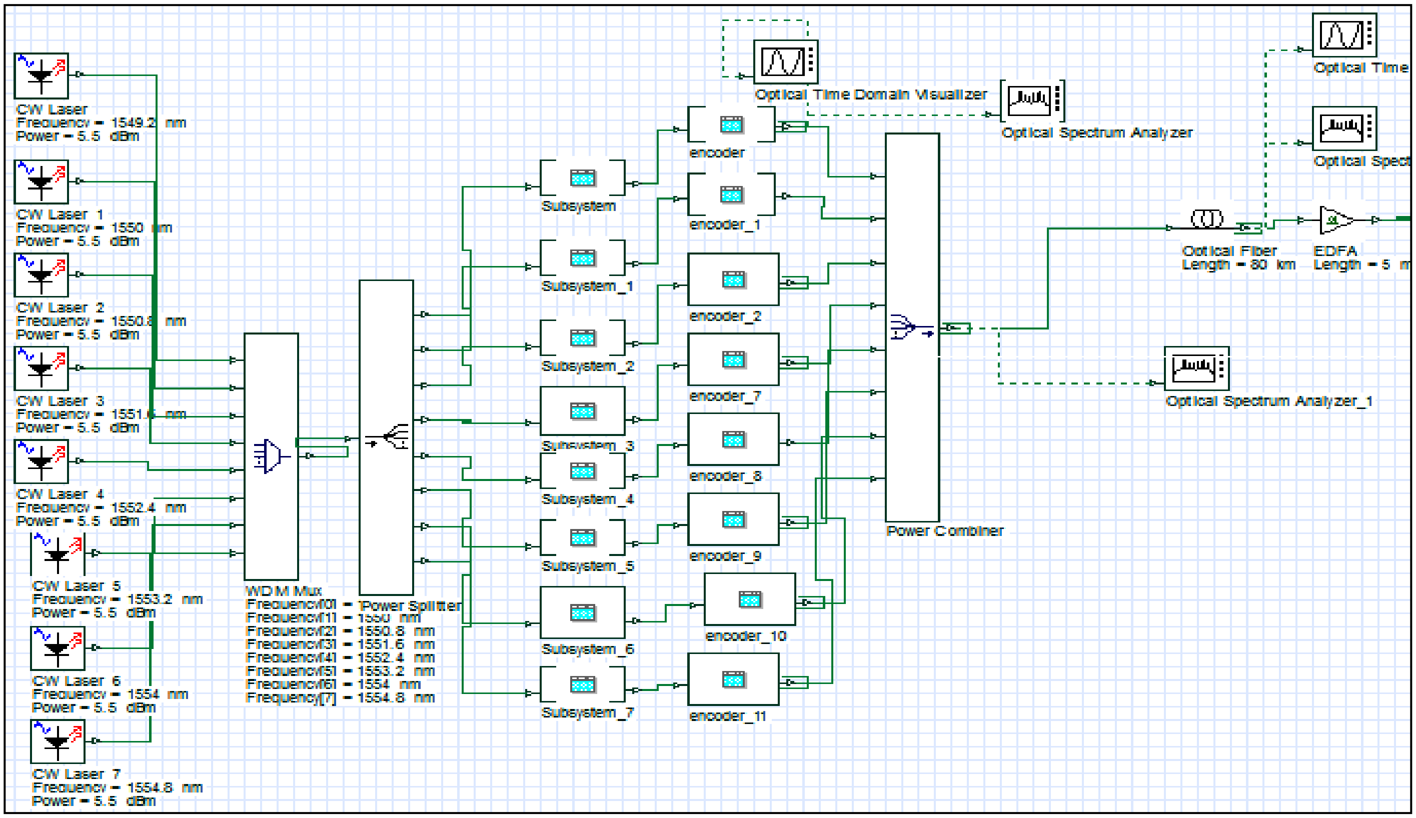


Fig. 7. OCDMA Transmitter block on Optisystem

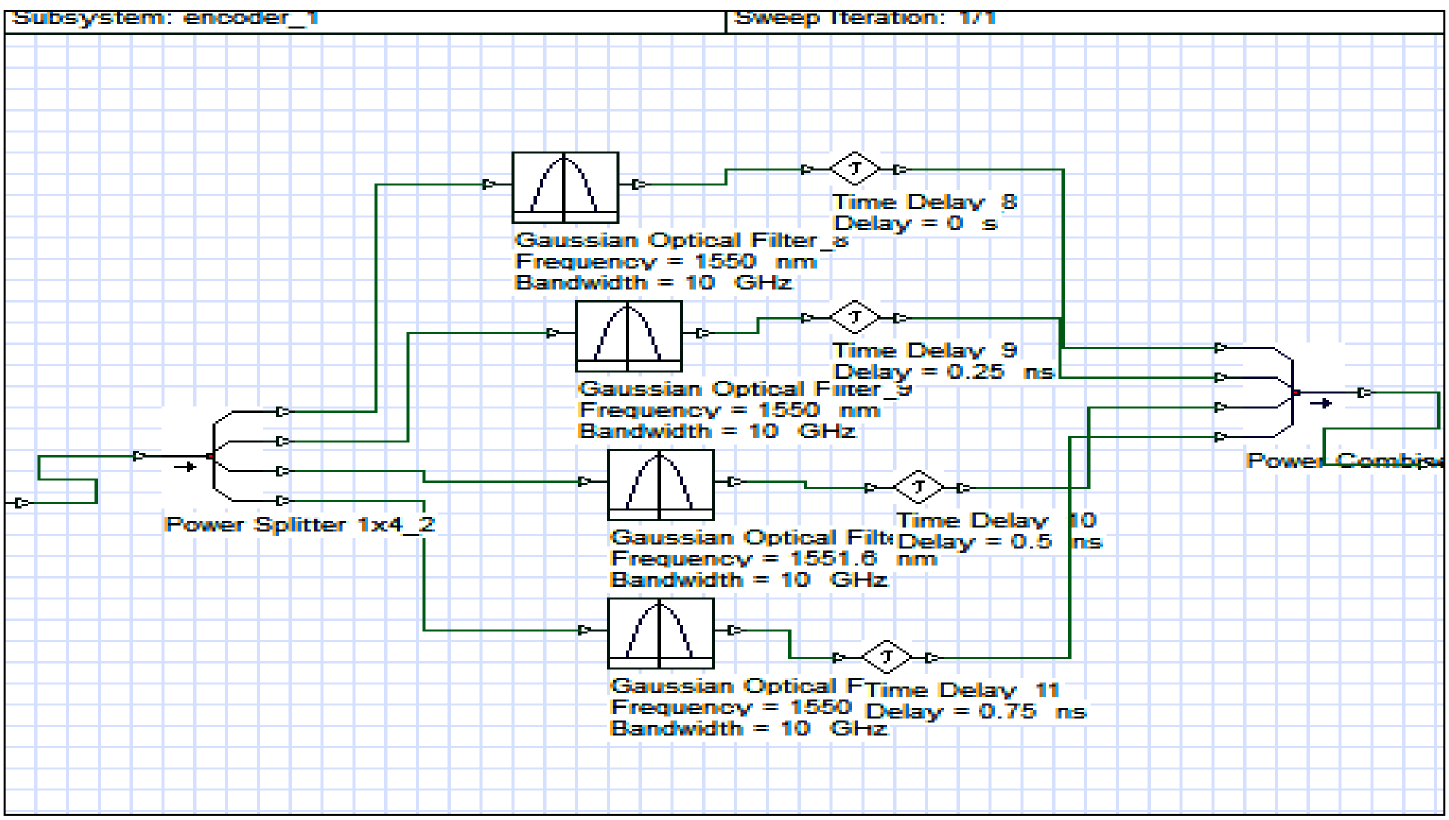


Fig. 8. Encoder Structure on Optisystem

TABLE I. TRANSMITTER DESIGN PARAMETER

Component	Parameter	Value
CW Laser	Wavelength	1549.2 nm
	Spacing	0.8 nm
	Power	5.5 dBm
	Line Width	10 MHz
	Initial Phase	0 degree
Pseudo Random Bit Sequence	Bit Rate	1 and 1.25 Gbps
Mach-Zehender Modulator	Excitation ratio	30 dB
Fiber	length	50 km
	Attenuation	0.2 dB/km
	Reference wavelength	1550 nm

The encoded data is combined and passed through single mode optical fiber (SMF) by considering length of 50 Km. Optical CDMA systems is designed which considers all practical impairments. The Table 3 represents time delay at 1 Gbps and 1.25 Gbps. If data rate is 1 Gbps that means the duration of 1 bit is 1 ns and since four time slots are taken, so the duration for each time slots will be 0.25 ns. For code M4 {λ_4 :λ_5 :λ_2:λ_1}, wavelength λ_4 is given in first time slot with zero delay, wavelength λ_5 is given in second time slot with 0.25 ns delay and wavelength λ_2 is given in third time slot with 0.5 ns delay and wavelength λ_1 is given in fourth time slot with 0.75 ns delay. Similarly delay for data rate 1.25 Gbps can also be calculated.

The optical signal is passed through the receiver section followed by decoder and photo detectors with low pass filter. The receiver extracts the information that is transmitted by transmitter. The decoder consists of optical filters and inverse time delays with respect to the transmitter that decodes a particular code as the corresponding encoder.

TABLE II. RECEIVER DESIGN PARAMETER

Chip Period	For 1Gbps bit rate (ns)	For 1.25 Gbps bit rate (ns)
T1	0	0
T2	0.25	0.2
T3	0.5	0.4
T4	0.75	0.6

TABLE III. TIME DELAY AT 1 GBPS AND 1.25 GBPS

Component	Parameter	Value
Photo-detector	Dark Current	10nA
	Center frequency	1552.5 nm
Low Pass Bessel Filter	Cutoff frequency	8 GHz
	Insertion loss	0 dB

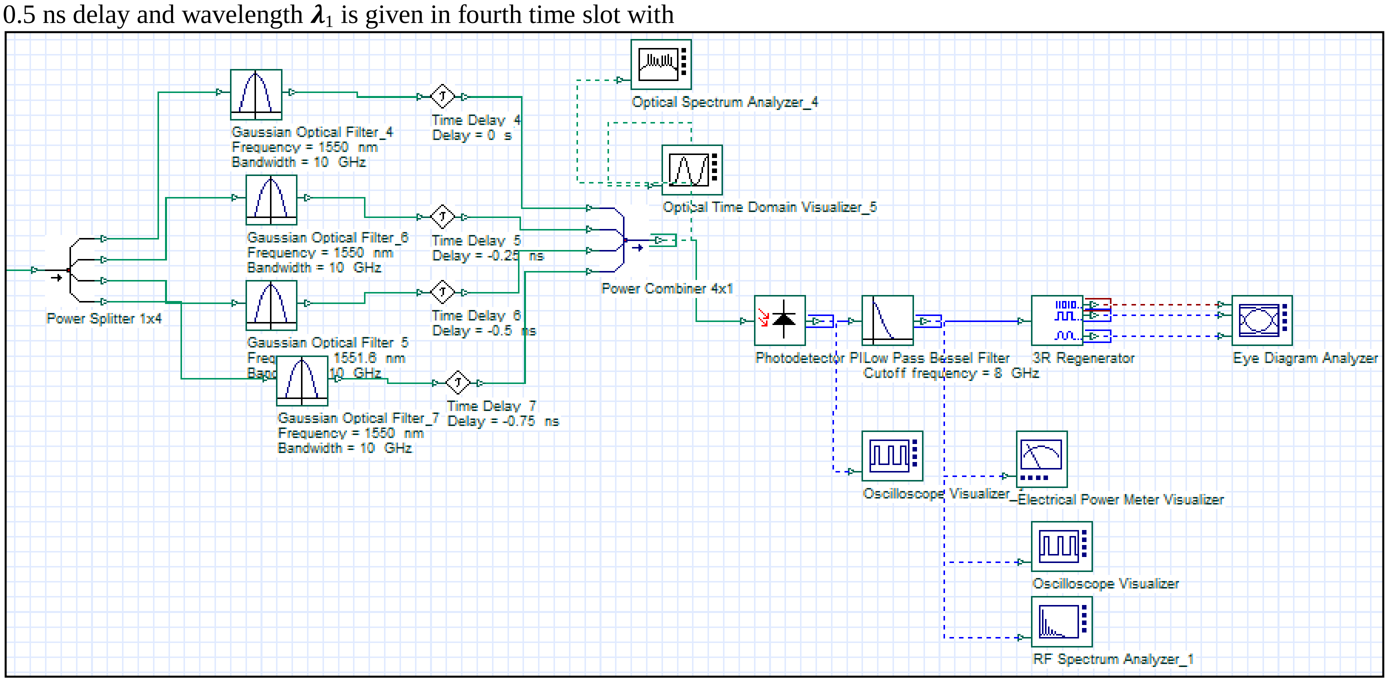
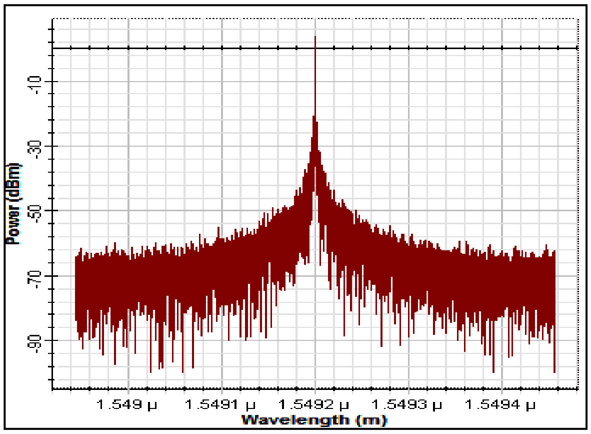


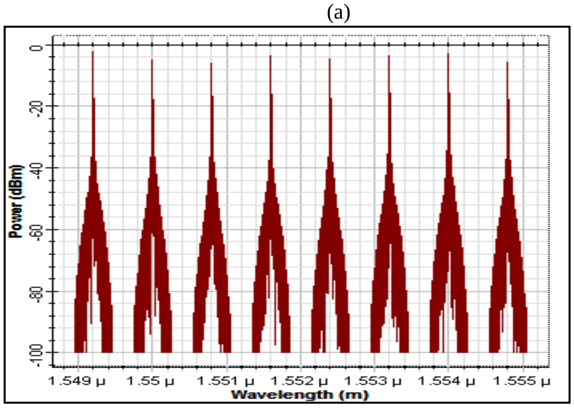
Fig. 9. OCDMA Receiver structure on Optisystem

V. Results and Discussions

The OCDMA system simulated on Optisystem uses CW laser centered at 1549.2 nm.



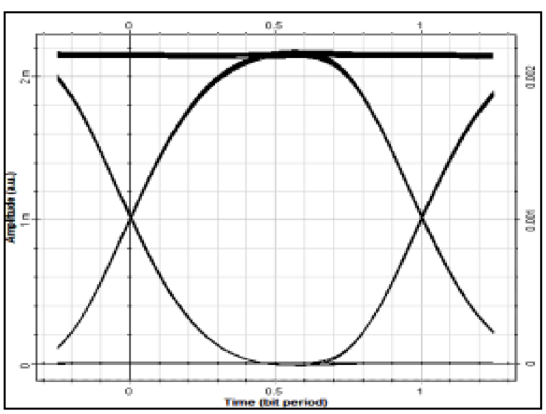
(a)



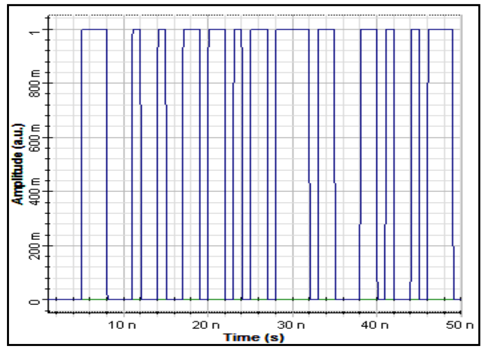
(b)

Fig. 10. CW Laser (a) Output of laser and (b) Multiplexed laser array spectrum

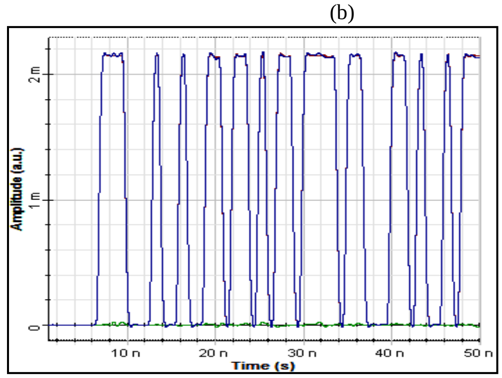
Figure 10 shows the CW laser output and eight multiplexed transmitted wavelengths. This multiplexed spectrum is modulated by user data with the help of MZM modulator. The output of MZM modulator is further encoded by different codes which are designed in Figure 6.



(a)

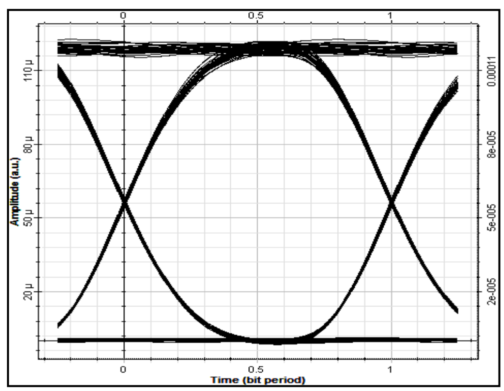


(b)

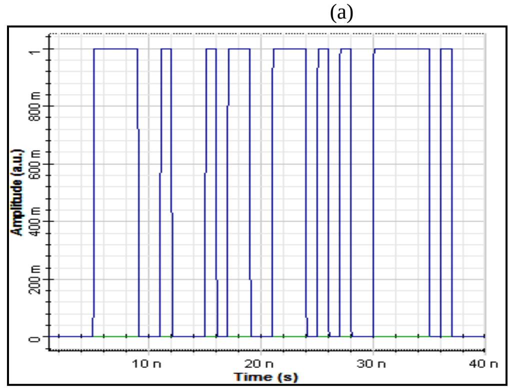


(c)

Fig. 11. Timing Diagram at 1Gbps for 1 user (a) Eye Diagram (b) Transmitted Signal (c) Received Signal



(a)



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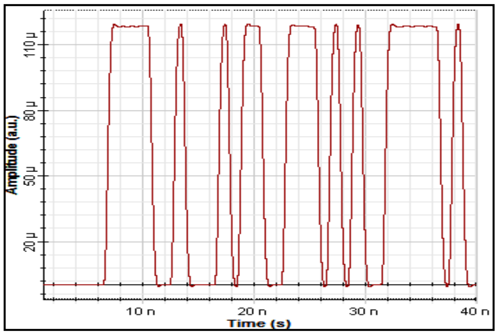
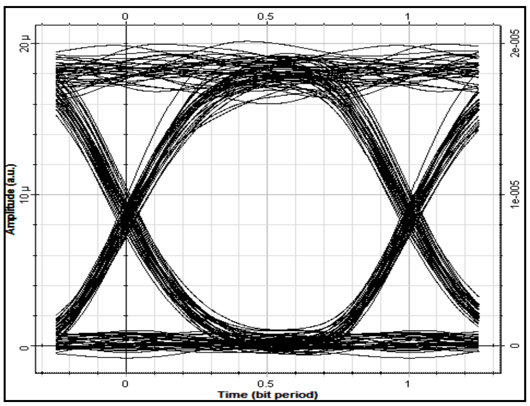
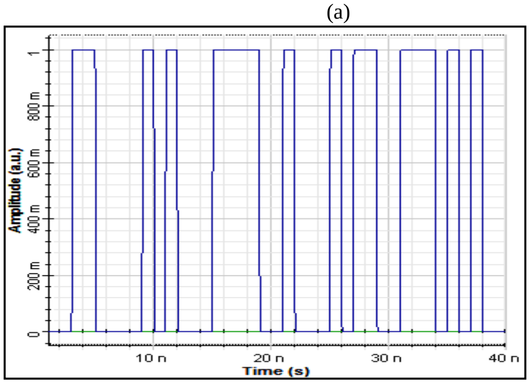


(c)

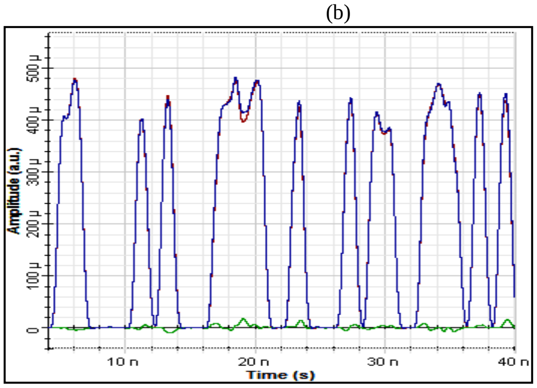
Fig. 12. Timing Diagram at 1Gbps for 3 users (a) Eye Diagram (b) Transmitted Signal (c) Received Signal



(a)

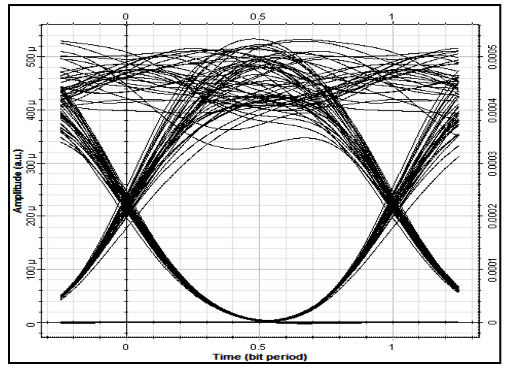


(b)

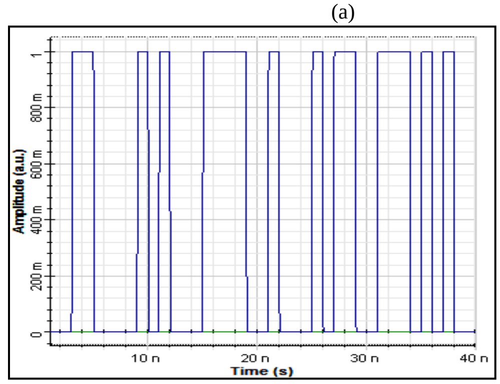


(c)

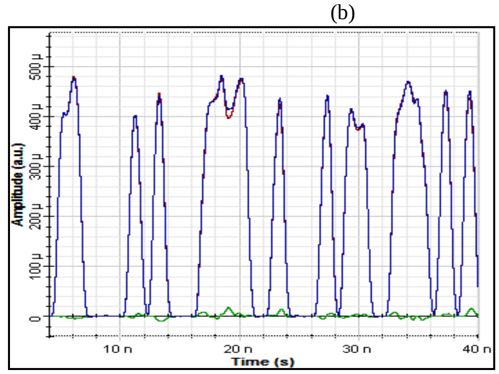
Fig. 13. Timing Diagram at 1Gbps for 8 users (a) Eye Diagram (b) Transmitted Signal (c) Received Signal



(a)



(b)



(c)

Fig. 14. Timing Diagram at 1Gbps for 12 users (a) Eye Diagram (b) Transmitted Signal (c) Received Signal

The demultiplexer demultiplexes the output which is given to the decoder section. The receiver receives the optical signal and converts it back to the electrical signal. The timing diagram at 1 Gbps for 1, 3, 8, and 12 users are shown in Figure 11 to Figure 14. The eye diagram allows visualizing the main parameters of electrical signal such as eye width, eye opening, quality factor, SNR etc. Figure 11- 14(a) represents the eye diagram. For an eye diagram measurement, noise on eye will cause the eye to close. Therefore the SNR is also directly indicated by amount of eye closer which represents that as the number of users increased the eye diagram starts closing means due to multiple access interference upper portion starts building noise. The Figure 11-14(b) represents the transmitted signal and Figure 11-14(c) represents the received signal. From Figure 11-14(a), it is revealed that as the number of users increase from 1 to 12, noise is added and the eye height start decreasing and from Figure 11-14(c), it is noted that there is some noise at the amplitude of the signal which result that the amplitude decreases almost to 400µ (a.u.) which is initially at 2000µ (a.u.) and the received signal is also dispersed in time domain as it passes through the fiber. Similarly signal can be received at 1.5 Gbps but as the data rate has been increased from 1 Gbps to 1.25 Gbps, MAI further increases.

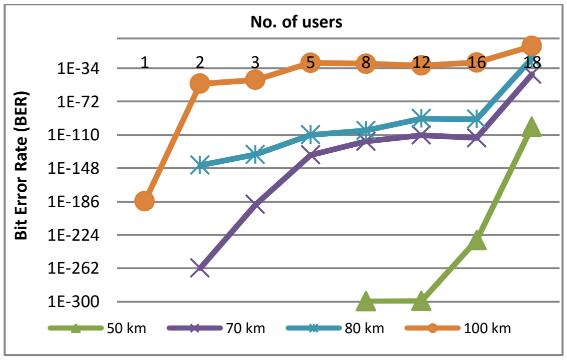


Fig. 15. BER vs. Number of users for different fiber length at 1 Gbps

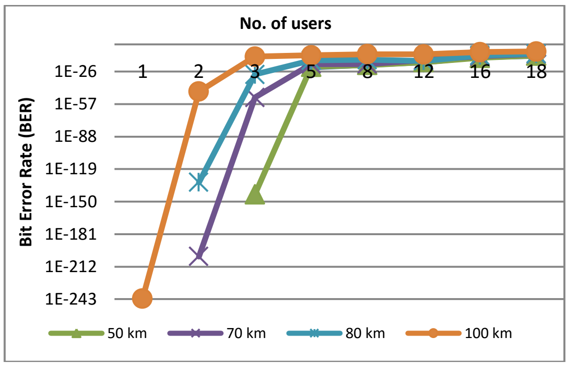


Fig. 16. BER vs. No. of users for different fiber length at 1.25 Gbps

The comparative analysis between BER and number of users for various lengths of fiber at 1 Gbps and 1.25 Gbps is shown in Figure 15 and Figure 16 respectively. It is observed that as the length of the fiber increases the bit error rate also increases. For three number of simultaneous users in 1Gbps system, the bit error rate increases from 0 to $1e^{-40}$ as the fiber length has been increased from 50 to 100 km whereas for 1.25Gbps system, the bit error rate increases from $1e^{-150}$ to $1e^{-15}$.

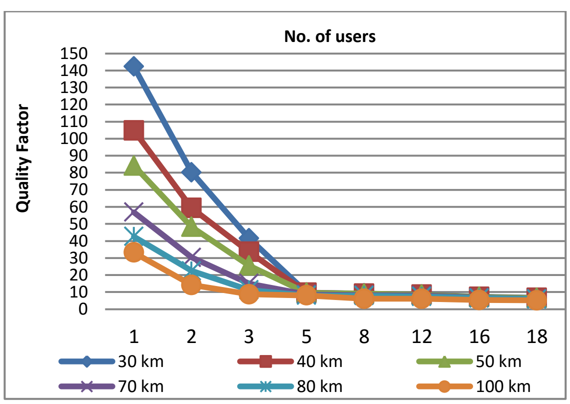


Fig. 17. Q factor vs. number of users for different fiber length at 1Gbps

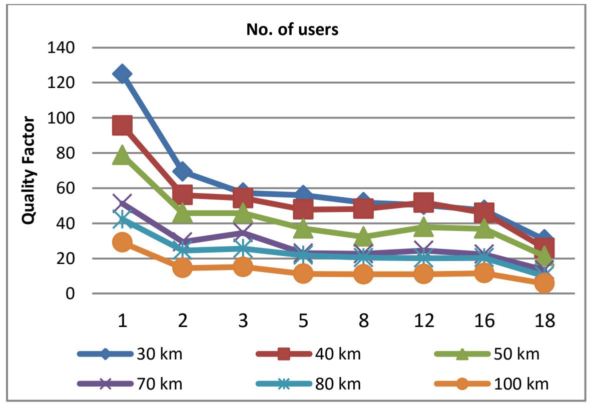


Fig. 18. Q factor vs. number of users for different fiber length at 1.25Gbps

The comparative analysis between quality factor and number of users for various lengths of fiber at 1 Gbps and 1.25 Gbps are presented in Figure 17 and Figure 18 respectively. It is observed that as the length of the fiber increases the quality factor decreases. For two simultaneous users in 1 Gbps system, the quality factor decreases from 80 to 10 as the fiber length increases from 30 to 100 Km whereas for 1.25 Gbps system, the quality factor decreases from 70 to 8. Similarly at data rate of 1.25 Gbps, the performance deteriorates. Hence, the analysis reveals that as the number of simultaneous users in the system increase, MAI become dominant with degrading in amplitude of received signal. For practical implementation of the optical CDMA based on the proposed codes, the optical fiber loop can be used instead of time delay line.

VI. Conclusion

One dimensional code have disadvantage of increasing code length with the increment of number of users. The simulated design of 2D W/T OCDMA code shows that cardinality of 2D code is high. The performance of OCDMA system has been evaluated with increasing number of users in the form of quality factor and BER .It has been observed that as the number of user's increases, the eye opening decreases which results in decrease in amplitude due to noise. At data rate of 1Gbps as the length of the fiber increases from 50 Km to 100 Km, the bit error rate shows the significant increment from 0 to e^{-40} with decrement of quality factor from 40 to 5 for 3 users.

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