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Implementation of Optical OFDM Based System for Optical Networks

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM), a frequency division multiplexing scheme utilized as a digital multi-carrier modulation technique, implemented using optical fiber link for practical applications thereby developing optical OFDM using OptSim simulation. OFDM has many advantages over other modulation techniques such as a high resistance to inter-symbol interference (ISI) and it is robust against fading caused by multipath propagation. Optical fiber cable (OFC) as a transmission media is used for distortion less transmission of data at a very higher data speed. OFC cable has a lot of advantages over other media. And OFDM over OFC cable will provide data speeds at a very high speed and with very less losses. In this work optical transmitter and receiver for OFDM based optical network has designed for high speed data transmission over optical fiber. While modeling the system we have also used post, pre and symmetric compensation technique to reconfigure the bandwidth along with add drop multiplexer, tunable filters and optical amplifiers to achieve high performance with minimum distortion and low bit error rate (BER).

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1. INTRODUCTION

In order to exploit optical bandwidth with more efficiently, recently optical OFDM as a special case of optical sub carrier modulation (SCM) was introduced in the optical domain, and an advanced optical OFDM (OOFDM) modulation technique was proposed [1], [2]. One of the main reasons for suitability of OFDM in optical communications is its ability to deal with large pulse spreads due to chromatic dispersion (CD) by dividing the broad optical channel spectrum (for which the dispersion effect is large) into a number of sub-channels each with a narrow spectrum which decreases the dispersion effect for each sub-channel [3], [4]. A main motivation for introducing OFDM in the optical domain is the possibility for high-speed data transmission over dispersive fiber without the need for costly optical dispersion compensation techniques [5].

The basic concept behind OFDM is the division of a high bit rate data stream into several low bit rate streams, which are simultaneously modulated onto orthogonal subcarriers as shown below in Figure 1. In general, the sub-carriers are generated in the digital domain and therefore these systems typically consist of many subcarriers (typically more than 50). In these systems, channel estimation is realized by periodically inserting training symbols. In fiber-optic transmission systems, the OFDM systems where the subcarriers are generated in the optical domain are also proposed. These systems are sometimes referred to as coherent wavelength division multiplexing (CO-WDM) systems. Coherent WDM systems typically have few subcarriers and do not use training symbols, but rely on blind channel estimation instead [6], [7], [8], [9].

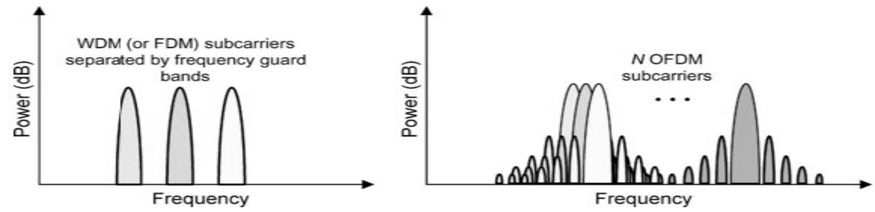


Figure 1. Spectrum of FDM & OFDM signal

1.1 Mathematical Formulation of an OFDM Signal

OFDM is a special class of multi carrier modulation (MCM) [10], [11], [12]. The MCM transmitted signal s(t) is represented as given in equations 1, 2 and 3.

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{sc}} C_{ki} S_k(t - iT_s) \tag{1}$$

$$S_k(t) = \prod(t)\, exp^{j2\pi f_k t} \tag{2}$$

$$\prod(t) = \begin{cases} 1, (0 < t \leq \mathrm{T_s}) \\ 0, (t \leq 0, t > T_s) \end{cases} \tag{3}$$

Where C_{ki} is the information symbol at the k^{th} subcarrier, S_k is the waveform for the k^{th} subcarrier, N_{sc} is the number of subcarrier, f_k is the frequency of the subcarrier and T_s is the symbol period, $\prod$ (t) is the pulse shaping function.

1.2 Spectral Effciency for Optical OFDM

In direct detection optical OFDM (DDO-OFDM) systems, the optical spectrum is usually not a linear replica of the radio frequency (RF) spectrum therefore; the optical spectral efficiency is dependent on the detailed implementation. These works concentrate on the optical spectral efficiency for coherent optical-OFDM (CO-OFDM) systems [13], [14], [15], [16]. In CO-OFDM systems, N_{sc} subcarriers are transmitted in every OFDM symbol period of T_s. Thus, the total symbol rate R for CO-OFDM systems is given by equation 4.

$$R = \frac{N_{sc}}{T_s} \tag{4}$$

The below Figure 2 (a) shows the spectrum of wavelength-division multiplexed (WDM) channels, each with CO-OFDM modulation, and Figure 2 (b) shows the zoomed-in optical spectrum for each wavelength channel. It uses the bandwidth of the first null to denote the boundary of each wavelength channel. The Figure 2 (b) shows OFDM bandwidth, B_{OFDM}, is thus given by equation 5.

$$B_{OFDM} = \frac{2}{T_s} + \frac{N_{sc} - 1}{t_s} \tag{5}$$

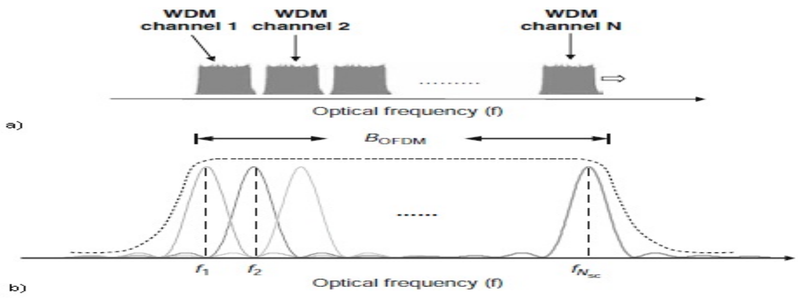


Figure 2. Optical Spectrum for (a) N- wavelength division multiplexed CO-OFDM channels, (b) Zoomed-in OFDM signal for one wavelength

Where t_s is the observation period as shown in Figure 3. Assuming that a large number of subcarriers are used, the bandwidth efficiency of OFDM is found to be given by equation 6.

$$\eta = 2\frac{R}{B_{OFDM}} = 2\alpha, \alpha = \frac{t_s}{T_s} \quad (6)$$

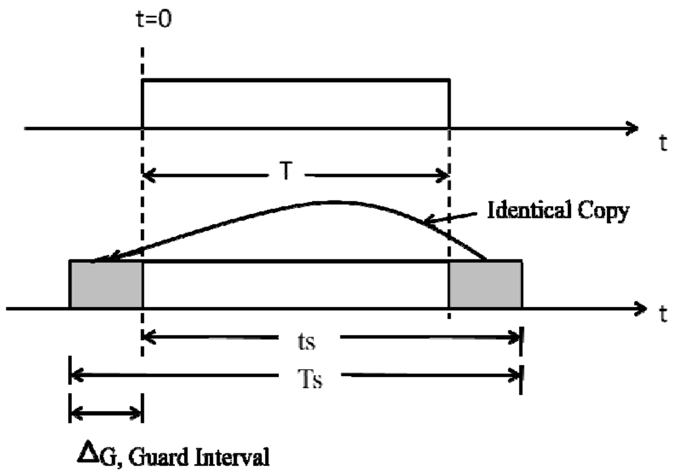


Figure 3. Time domain OFDM signal for one complete OFDM symbol

The factor of 2 accounts for two polarizations in the fiber. Using a typical value of 8/9, to obtain the optical spectral efficiency factor of 1.8 dB/Hz. The optical spectral efficiency gives 3.6 bit/s/Hz if quaternary phase-shift keying (QPSK) modulation is used for each subcarrier. The spectral efficiency can be further improved by using higher order QAM modulation to practically implement CO-OFDM systems, the optical spectral efficiency will be reduced due to the need for a sufficient guard band between WDM channels, taking account of laser frequency drift of approximately 2 GHz. This guard band can be avoided by using orthogonality across the WDM channels.

1.3 Optical OFDM Basics

1.3.1 Cross-channel OFDM: multiplexing without guard band

The laser frequency drift of WDM channels can be resolved by locking all the lasers to the common optical standard such as an optical comb and directly using the frequency tones from an optical comb. All the subcarriers that cross the WDM channels can be orthogonal; that is, the orthogonality condition is satisfied for any two subcarriers, even from different WDM channels. As shown in Figure 4 cross-channel OFDM (XC-OFDM) without guard band, the subcarrier in channel 1 is orthogonal to another subcarrier in a different channel.

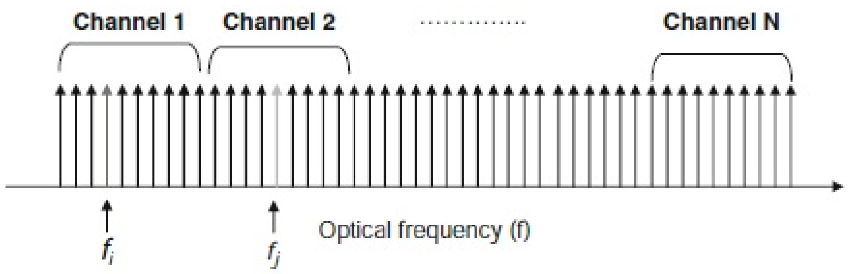


Figure 4. Optical spectrum for division cross-channel OFDM (XC-OFDM) without guard band

2. BLOCK DIAGRAM OF OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OOFDM)

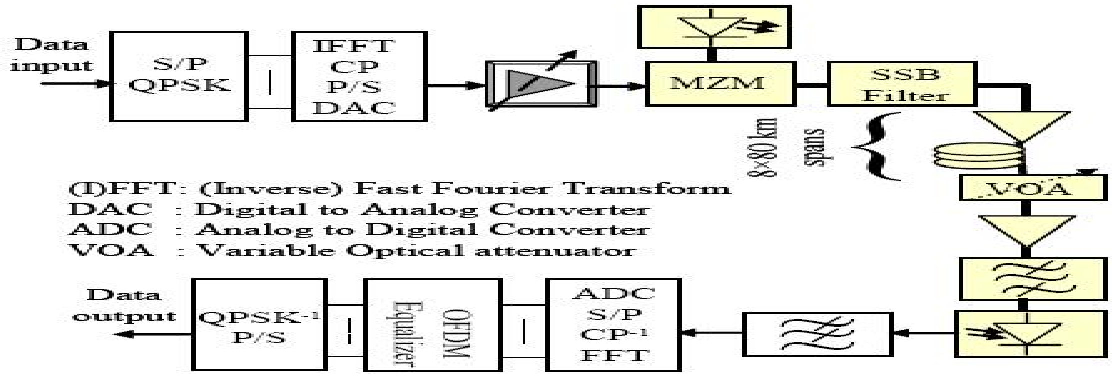


Figure 5. OOFDM simulation setup

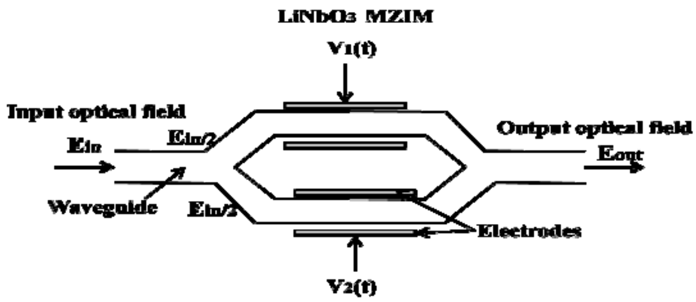


Figure 6. Dual drive MZIM

The MZM used in the above block diagram Figure 5 is dual drive MZM. A dual drive Mach-Zehnder inferometer modulator (MZIM) is chirp free modulator is shown in above Figure 6. The MZIM used in the Figure 6 is Lithium Niobate based, the purpose of choosing this material is i) It is electro optic in nature ii) Less loss MZIM used here is of “Z” cut. Its essential that the MZIM has a typical phase response, such that it will function as a modulator effectively in the above set up.

The Figure 6 shows the ‘Y’ branch intensity modulator. The hatched region is a switching part on which the phase retardation of the light (actually refractive index of the wave-guide) is varied. The device parameters are angular separation between the arms 22^0, Index difference of 2.3 % gap between the electrodes is 4 μm length of the arm 20000 μm, $V\pi = 5$ V.

When the refractive index of the switching region is not varied, the two light beams are combined with same phase retardation (In phase) at the 'Y' combiner. Therefore almost 100 % light transmission is achieved in the output wave-guide, as shown in the Figure 7 (a). This condition is known as constructive interference. When the refractive index of the switching region is varied by δn, the relative phase retardation between the two arms becomes (φ = δβ.L) where L denotes the length of the switching region, i.e. two parallel arms. If the relative phase retardation satisfies equation 7.

$$\delta\beta.L = \frac{2\pi}{\lambda}\delta_{neff}.L = \pi \tag{7}$$

Then the two light beams are combined with an out of phase condition at the "Y" combiner as shown in the Figure 7 (b). This condition is known as destructive interference. Here the δn_{eff} is a variation of effective index. Once the intensity modulation is achieved OFDM signals are fed as $V_1(t)$ and $V_2(t)$. As we require orthogonal signals.

Essentially there are two simulation set up for OFDM. i) Phase modulated OFDM system, ii) Amplitude modulated OFDM system. In our study, we have considered phase modulated and ampllitude OFDM. Two simulation set up for phase modulated OFDM system and amplitude modulated system are depicted in Figure 8 and Figure 9.

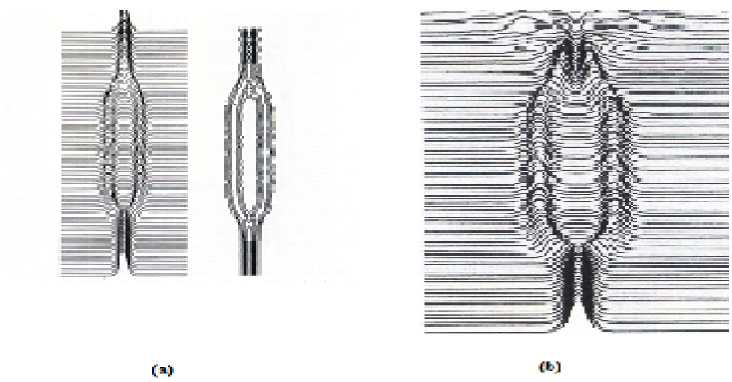


Figure 7. a) Contructive interference for zero phase shift, b) Destructive interference for π phase shift

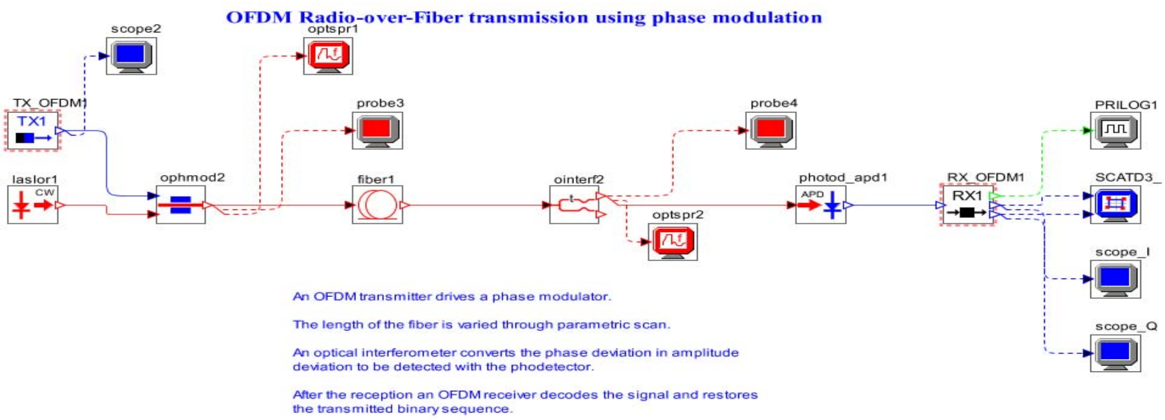


Figure 8. Block diagram of optical OFDM system using phase modulation

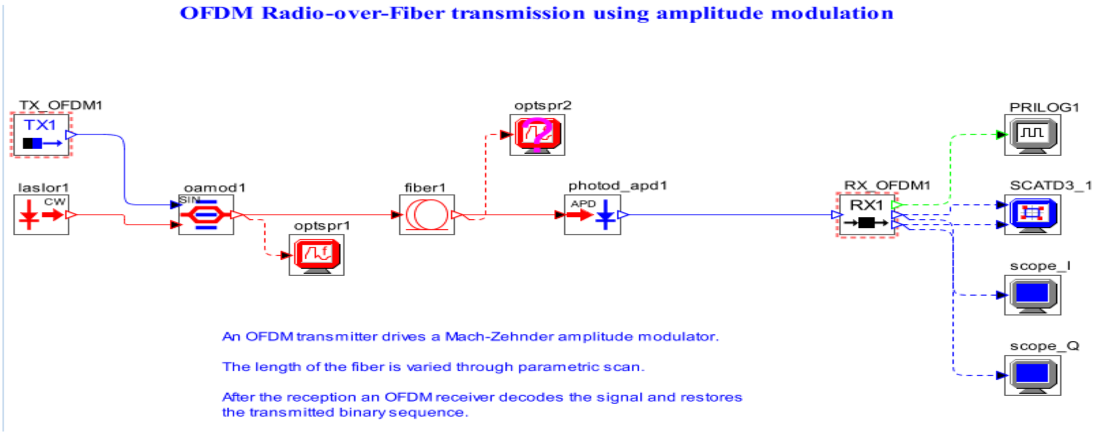


Figure 9. Block diagram of an optical OFDM system using amplitude modulation

The Figure 8 and Figure 9 shows a block diagram of fiber optic communication system based on optical OFDM, in which the FT blocks are implemented in optical domain using the Fourier transforming property of time lenses. In the proposed scheme, the combined signal drives the Mach-Zehnder modulator (MZM). In contrast, in the case of electrical OFDM, message signals from various channels modulate the sub-carriers through IFFT. The output of the fiber-optic link passes through a FT. Since Fourier transform of a Fourier transform leads to time reversal within a OFDM frame, the transmitted signal can be recovered by introducing time reversal using digital signal processing. In the case of coherent optical/electrical OFDM, a phase chirp is introduced across the frame due to fiber dispersive effects which can be cancelled using equalization algorithms. However, in the case of direct detection equalizer is not needed, since the output of the direct detection receiver is proportional to the absolute square of the field envelope. To investigate the performance of the optical OFDM, both coherent and direct detection schemes are simulated and the bit error rate (BER) is calculated at the receiver as a function of optical signal-to-noise ratio (OSNR). The OSNR is calculated based on 0.1 nm noise bandwidth. Fiber nonlinearity and amplified spontaneous emission (ASE) noise are both taken into account in the simulation. The number of sub-channels is 2048 and the cyclic prefix of length 512 is added as the guard interval between OFDM frames. Each of the sub-channels consists of a BPSK signal at a bit rate of 19.5 Mb/s and the total information rate is 40 Gb/s. In the case of direct detection OFDM, a constant bias voltage is added at the input of MZM so that the output of MZM is an on-off keying (OOK) signal. The transmission fiber is a standard single-mode fiber (SSMF). The parameters of the fiber and other system components are listed. There is no dispersion compensating module (DCM) placed in the fiber link. The amplifier span is 80 km with 5 spans, so the total transmission distance is 400 km. A De Bruijin sequence of length 211 is used in each of the sub-channel in the Monte-Carlo simulation and the total number of OFDM frames is 50. The accumulated dispersion $\beta_2 F$ in time-lens-based Fourier transformer is 0.1019 ns2, where F is the fiber length and β_2 is the dispersion of the standard SMF used in the time lens setup.

The two important building blocks of OOFDM system are transmitter and receiver. The component that constitutes the transmitter and receiver are presented in Figure 10 and Figure 11.

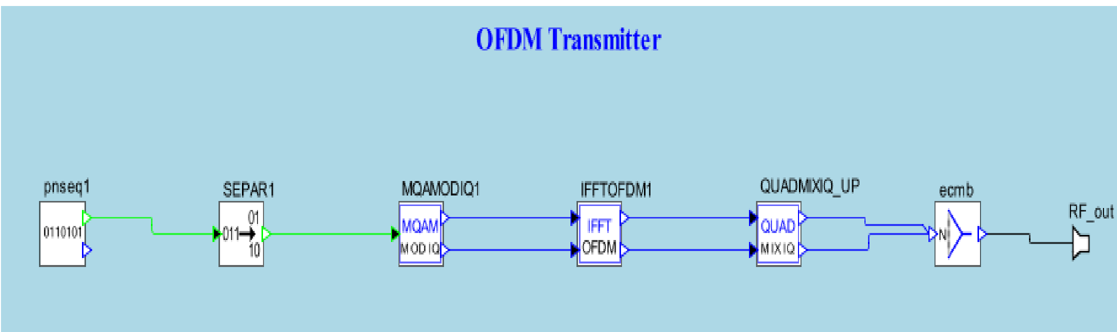


Figure 10. OFDM transmitter

This compound component simulates an OFDM transmitter composed of:
- PRBS data source
- SEPAR model to perform the conversion serial to parallel
- MQAMODIQ model to generate the baseband I/Q components of QAM symbol
- IFFT OFDM to calculate the IFFT on the QAM symbol and obtain the OFDM symbol
- QUADMIXIQ model to quadrature mix up the OFDM signal from baseband to carrier frequency

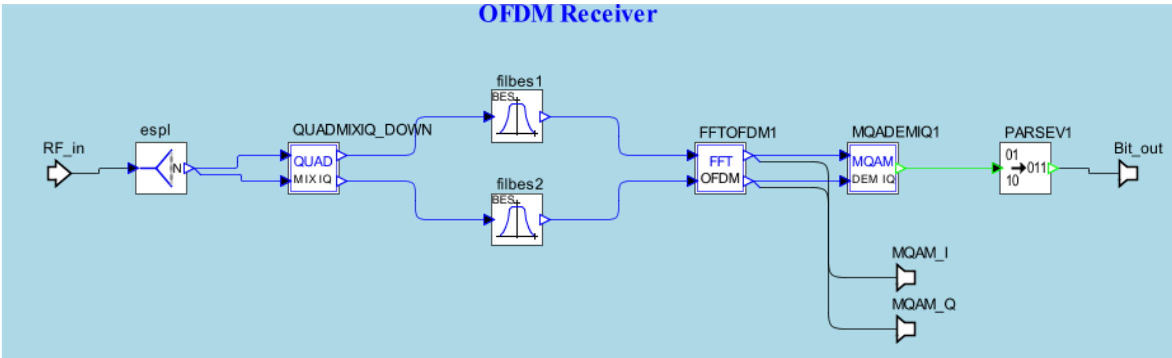


Figure 11. OFDM receiver

This compound component simulates an OFDM receiver composed of:
- QUADMIXIQ model to quadrature mix down the RF modulated OFDM signal to baseband
- Two Bessel filters to filter out the replica of the signal centered at twice the carrier frequency
- FFTOFDM model to calculate the FFT on the OFDM symbol to recover the QAM symbol
- MQADEMIQ model to retrieve the parallel logical signal from the QAM symbol
- PARSEV model to perform the conversion parallel to serial and restore the transmitted serial binary sequence

The optical phase modulator considered for simulation operates at reference wavelength 1550 nm with dispersion 16 ps/nm/km. The fiber considered here has 0.2 dB loss/km. The length = 3 km. The Laser source used here are of three types.
- a simple model considering only the phase noise (CW Lorentzian Laser)
- a realistic model based on rate equation integration (Rate Equations Laser)
- a realistic model based on rate equation integration for Separate confinement heterostructure multi quantum well lasers (SCH-MQW)

where physical parameters of the laser can be obtained with a fitting procedure over experimentally measured curves.

The detector section comprises of PIN and APD. The quantum efficiency, responsivity, dark current and 3 dB bandwidth values are 0.7, 0.8751, 2.5 nA and 20 GHz.

The Dispersion section defines the dispersion characteristics of the fiber. Second, third, fourth and fifth order dispersion coefficients are taken into account. You may directly specify the coefficient values or supply a description file. In the latter case the file must contain the profile of dispersion β_2 as a function of frequency or *D* as a function of wavelength. This feature is used to introduce data from a measured set of results. In addition, a random variation of the second order dispersion is taken into account using two different statistical distributions and a defined correlation length. The statistical variation of fiber dispersion is emulated by a cascade of short fiber spans the characteristics of which are defined at the beginning of a simulation. These characteristics do not vary during the simulation. A different random evolution of dispersion may be obtained by re-simulating the project with a different random seed. Furthermore while doing the simulations, SPT behaviour is considered. Laser sources are considered as if they generated a single tone at the nominal center emission frequency of the source. Therefore, in the optical spectrum a single line is placed. Its level is equal to the defined laser output power. Line width is neglected if the CW Lorentzian Laser is selected. For the rate equations laser and the custom multi quantum well (MQW) laser, their output power could be found only using time-domain simulation. Hence, for SPT simulations, the user is explicitly requested to supply the output power. If you don't know the average output power of the laser, we suggest perform a virtual battle space (VBS) simulation of the device only, measure the output power, and then employs the measured value as SPT parameter for the laser.

3. BLOCK DIAGRAM OF OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OOFDM) FOR BANDWIDTH RECONFIGURATIION

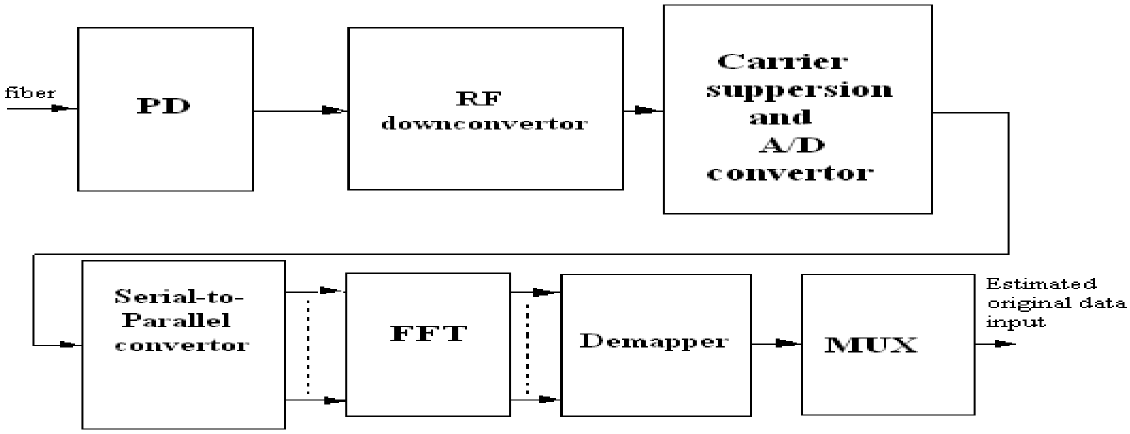


Figure 12. OFDM receiver with add drop multiplexer

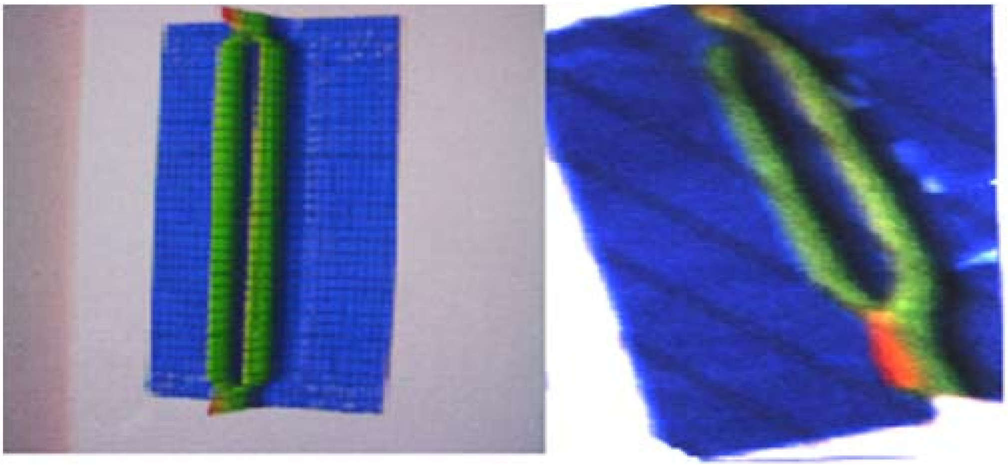
Inorder to enhance the performance of OOFDM link used in our simulation, we replaced the simple multiplexer by an add-drop multiplexer. We considered 10 Gb/s 16-channels wave length division multiplexing (WDM) system with a 4-channel s and optical add drop multiplexer (OADM) put in the middle of the fiber link.The transmitter consists of 16 laser sources with wavelength ranging from 193.035 THz to 193.785 THz, the channel spacing is set to 50 GHz for 200 km optical link. In this link shown in Fig 12, we used post, pre and symmetric compensation technique along with tunable filters and different optical amplifiers to enhance the performance.We used Fabry Perot filter in our module which offers tuning range of 30 nm in 1-10 ms.When we tested the link with EDFA and Raman amplifier, EDFA proved to be the best, offering wide power spectrum with a received power of 0.27 mw for an i/p of 1 mw for 200 km optical link.which can be detected using simple photo detector.

4. METHODOLOGY

We have used frequency domain simulation model using OptSim. Using Block model simulation mode, we could effeciively capture the dynamic and transient behavior of the optical network. For the choice of appropriate laser for our simulation, we used “Best fit” Laser tool kits. We interfaced OptSim model with “Beam Propagation model” to simulate and study the charectristics of Lihium Niobte based modulator to incorporate it in the network model. We took into consideration “polarization mode dispersion” (PMD) effect provided in “OptiSim model”. We have used various optical ampliers designed using built in facility of this software. For various types of optical amplifiers, the simulation was carried out. To combat dispersion, we used post, pre and symmetric compenstion technique and observed the eye pattern and compared the BER performance in above mentioned three cases. By comparing with earlier findings, where the PMD was not taken into consideration, we proved that opical OFDM with PMD consideration offers optimum value of BER thus validating our results.

5. RESULTS AND DISCUSSION

In order to achieve a proper OFDM spectrum, it’s very essential that the phase shift offered by the modulator is accurate. The modulator is simulated at the component level. Its response is observed and the same parameters are considered while simulating the OFDM block diagram. The response is shown in Figure 13 (a) and (b).



(a) (b)

Figure 13. a) Propagation of light for zero phase shifts, b) Propagation of light when phase shift is introduced when OFDM signal is fed

The phase response of the modulator included in the OFDM block diagram is presented in Figure 13.

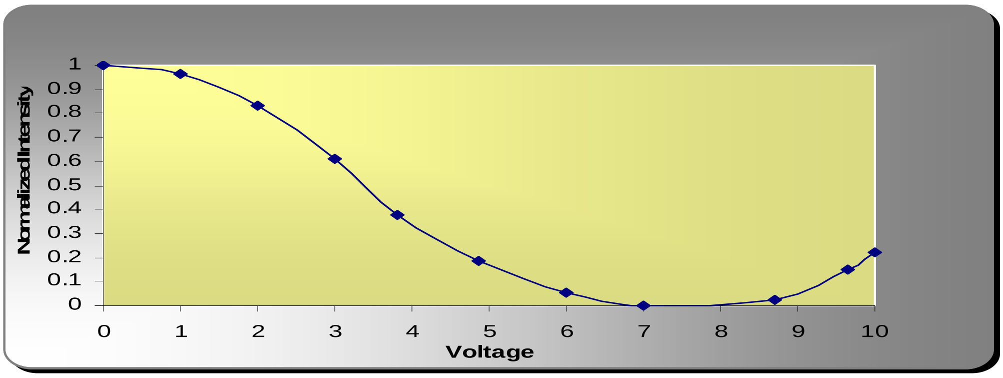


Figure 14. Variation of intensity with the applied voltage

The modulator used in our study is proton exchanged $LiNbO_3$, whose surface index change (Δn_e) is linear and the variation of extraodinary refractive index change with applied voltage is optimum to exploit the largest electro-optic coefficient r_{33} for the TE polarized light. This is shown in Figure 14 and Figure 15.

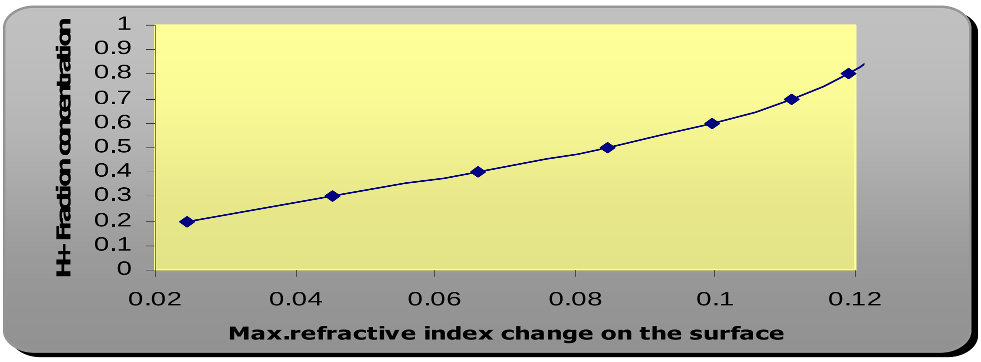


Figure 15. Surface index change (Δn_e) verses mole fraction

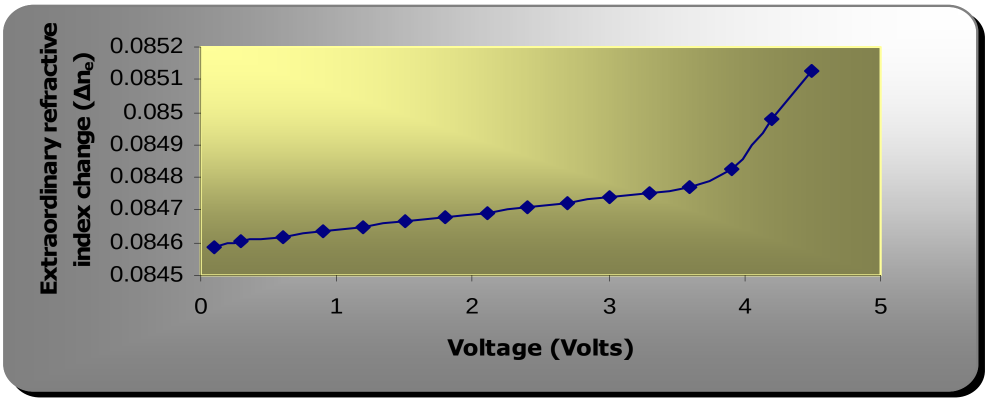


Figure 16. Extraordinary refractive index changes verses applied voltage

The above results shown in Figure 14 and Figure 15, ensures that modulator used in our OFDM simulation block provides optimum phase shift to generate the OFDM signal in the optical domain. This simulation results are used in the OFDM simulation window to evaluate the transmitted and received signal power spectrum for quadratue amplitude modulation (QAM) signal followed by the constellation diagram.

By comparing the transmitted and received power spectrum of the OFDM symbol as shown in Figure 17, 18 and 19 and the corresponding constellation diagram shown in Figure 20. It shows that the transmitter and receiver power spectrum are nearly identical as shown in Figure 17 and 18. Altough 5 spans of fiber length are considered, we infer from the results that inter-symbol interference (ISI) is minimum, minimal loss, optical power level is high and we are able to maximize SNR with four optical amplifiers. In the super imposed power spectrum as shown in Figure 19, the green spectrum is the transmitted signal whereas the red spectrum is the received signal. The receiver power spectrum is distorted due to the various fiber losses and attenuation caused by the fiber over long distances. However, we observe that delay spread is less than one symbol period thus minimizing the inter-carrier interference and enhancing the spectral efficiency. The plot obtained is of a 16 bit QAM signal.

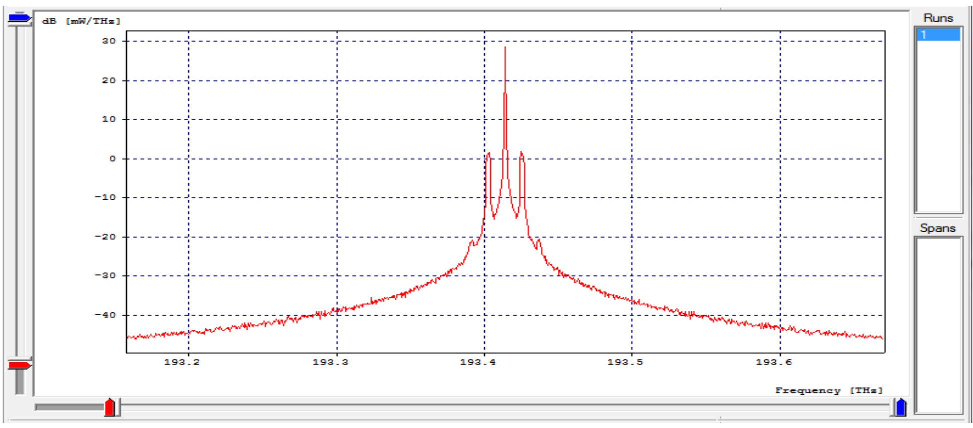


Figure 17. Transmitted OFDM power spectrum.

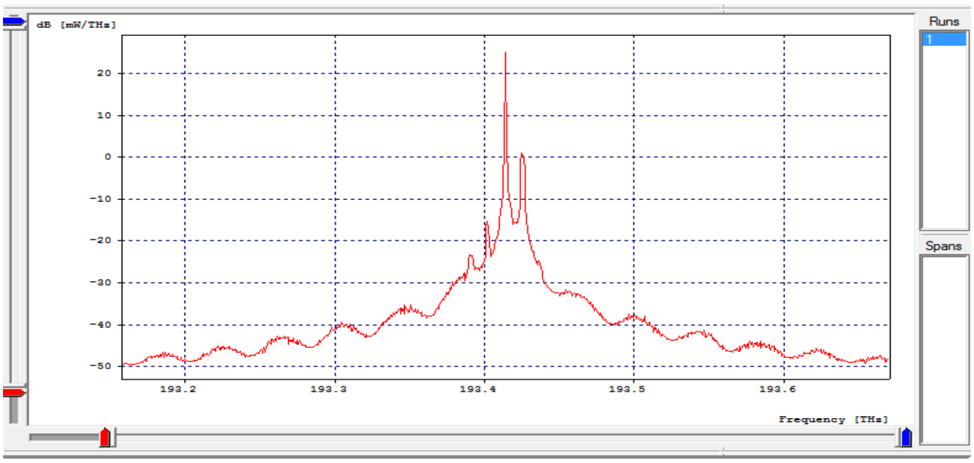


Figure 18. Received OFDM power spectrum.

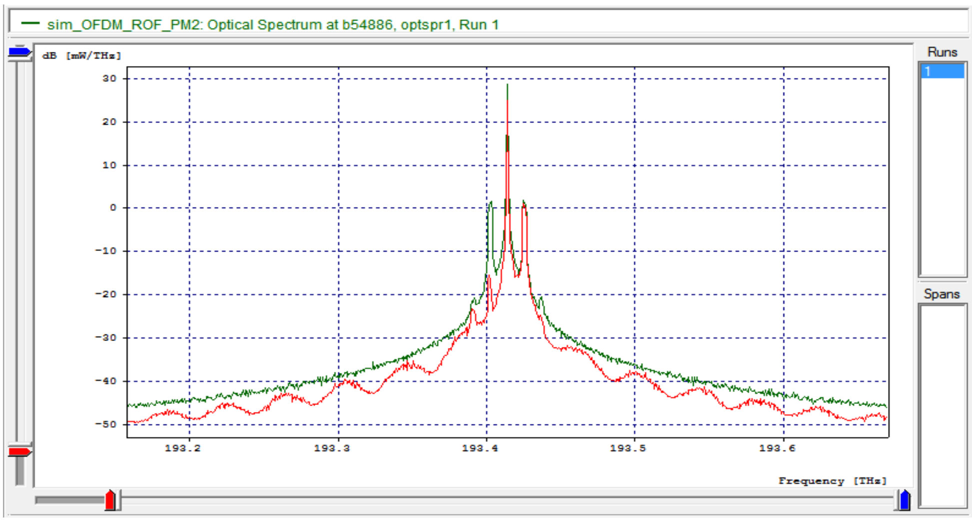


Figure 19. Superimposed power spectrum of transmitter and receiver

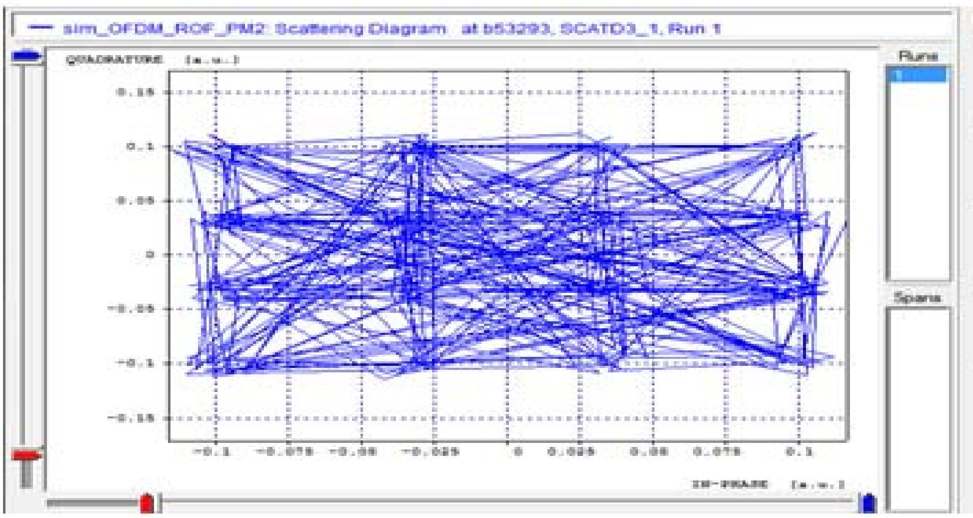


Figure 20. Scatter plot for digital modulation

When 10 Gbps Non Return to Zero (NRZ) signal is launched into the link and applied pre, post and symmetric compenstaion technique we observed better performnce.This is accertained by the eye diagram shown in Figure 21, Figure 22 and Figure 23.

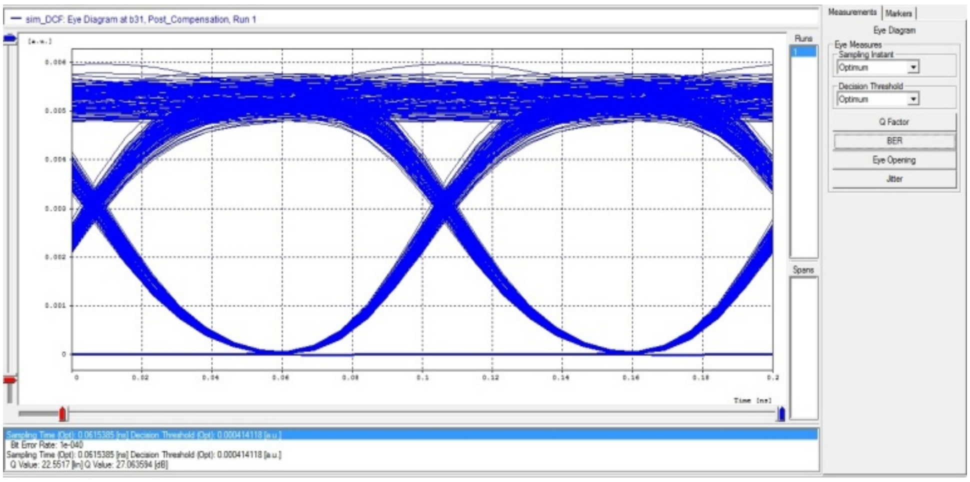


Figure 21. Post compensation eye diagram for 10 Gbps NRZ link

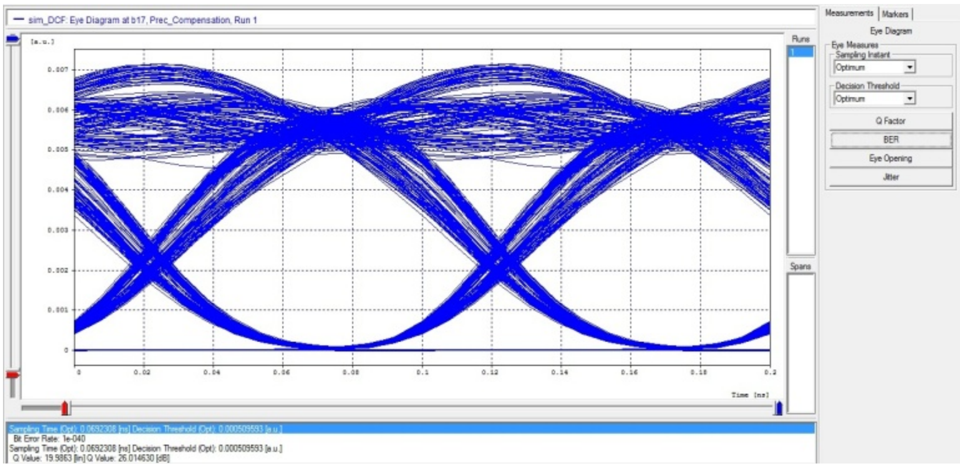


Figure 22. Pre compensation eye diagram for 10 Gbps NRZ link

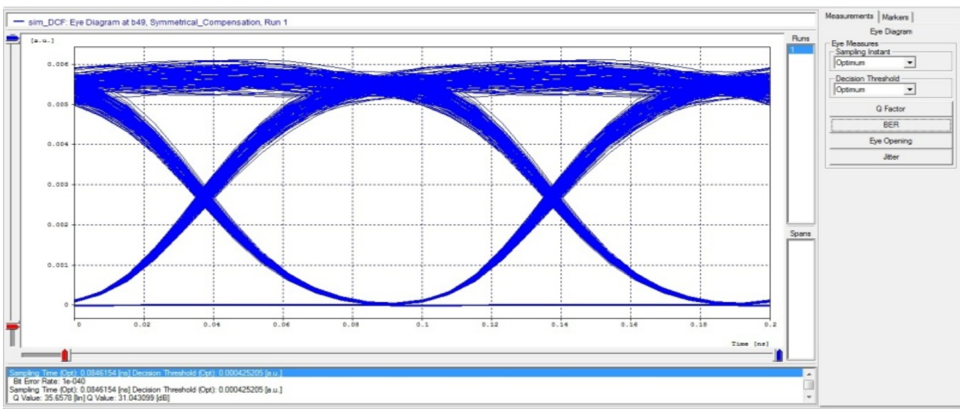


Figure 23. Symmetric compensation eye diagram for 10 Gbps NRZ link

After observing the eye diagram for all three compensation technique, for a fixed EDFA gain, a sequence length of 1024 bits, it is ascertained that symmetric compensation surpasses others in terms of eye closure penalty and bit error rate as shown in Figure 24.

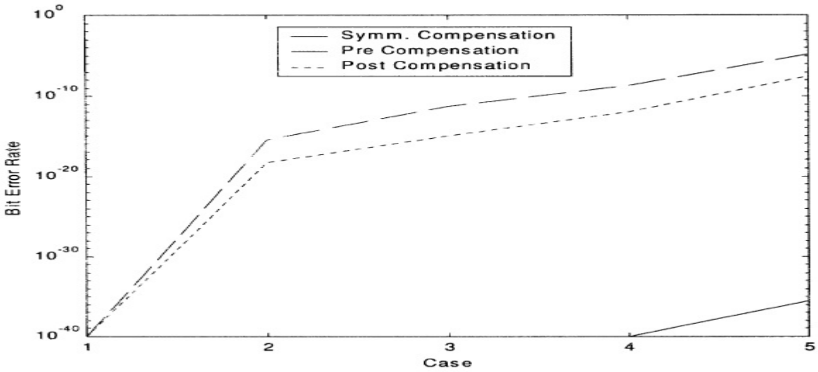


Figure 24. BER performance for all compensation techniques

We considered 10 Gb/s 16-channels WDM system with a 4-channel OADM put in the middle of the fiber link.The transmitter consists of 16-laser sources with wavelength ranging from 193.035 THz to 193.785 THz, the channel spacing is set to 50 GHz. The optical signal is launched onto a 200 Km fiber link. Along the fiber link, after 100 km, a 4- channel OADM is used to select and to add channels. The dropped channels are detected by the receivers with an appropriate electrical filtering. The added Channels are propagated together with the other ones and detected at the end of the fiber link.We computed the BER and “Q” value for the dropped channel. The “Q” value for the dropped channel is 25.51dB and BER-1 exp(-40). Wherin for other channels “Q” > 20dB, which ensures high value of BER due to bandwidth reconfiguration.Therefore the eye diagram for the added channel is better than the dropped channel as shown in Figure 25 and Figure 26.

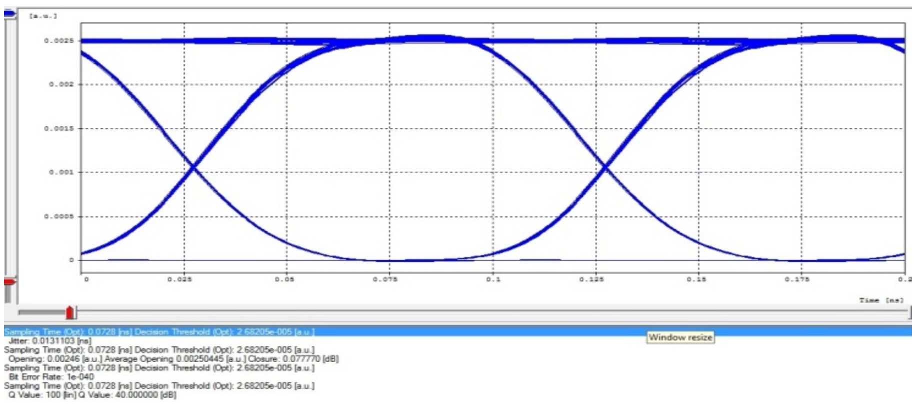


Figure 25. Eye diagram for the added channel

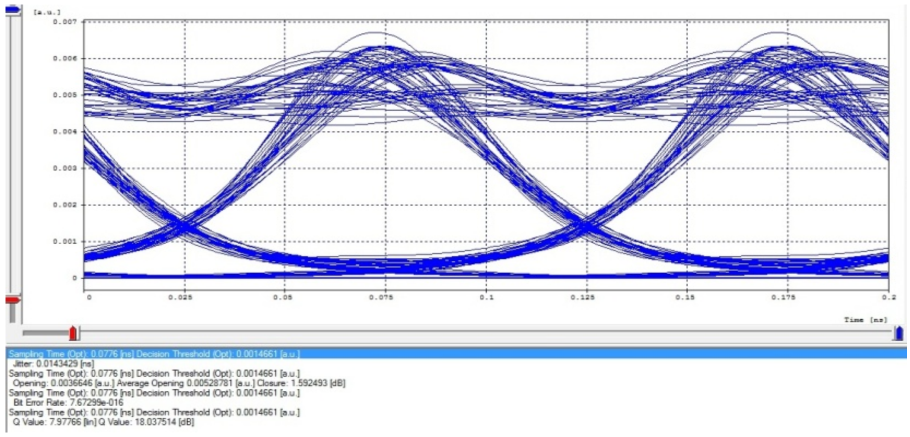


Figure 26. Eye diagram for the dropped channel

6. CONCLUSION

Optical OFDM is a fast-progressing and vibrant research field in optical communications. It is exciting that the most advanced communication concept and theory in modulation, coding, reception, and channel capacity is being applied in the optical domain, as has taken place in the wireless counterpart, but with the major distinction that the signal is processed at a much higher speed that approaches 1 Tb/s. This presents tremendous challenges and opportunities in the field of high-speed electronics and photonics. However, we are able to achieve negligible capacity decay as compared to 2 - 3 bits/Hz for 5 fiber span as reported in the litereature without using any dispersion compensation. This is due to QAM technique and simulating the link for dual polarization, taking into consideration polarization dependent losses, maintaining perfect and nonlinear effect, although it can be ignored for 4 - 5 spans of fiber. When dispersion techniques are employed we could increase the length of the link with minimum distortion.Furthermore when tunable filters and add drop filters are used along with EDFA, BER performance is enhanced.This result could be achieved without using the QAM technique.

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