



Electronic Signal Processing for Cancellation of Optical Systems Impairments

Asst. Prof. Dr. Ali Y. Fattah¹, Zainab Faydh Mohammed¹

¹Electrical Eng. Department, University of Technology, Baghdad

email: dralifattah@yahoo.com, zainab.faydh@yahoo.com

Received: 28/11/2012

Accepted: 22/07/2013

Abstract – In this paper 40 Gb/s DP-QPSK system with coherent reception and DSP unit for optical fiber impairments compensation is proposed. The DSP unit processes the detected coherent DP-QPSK signal. The Chromatic Dispersion (CD) is compensated using a simple transversal digital filter and Polarization Mode Dispersion (PMD) is compensated using adaptive butterfly equalizer which is realized by applying the constant-modulus algorithm (CMA). A nonlinear compensator (NLC) is used for compensating the nonlinear effects based on the technique of multi-span back-propagation. A modified Viterbi-and-Viterbi phase estimation algorithm (working jointly on both polarizations) is then used to compensate for phase and frequency mismatch between the transmitter and local oscillator (LO). After the digital signal processing is complete, the signal is sent to the detector and decoder, and then to the BER test set for direct-error-counting. The presented system is designed and simulated using OptiSystem (2011) software interfaced with MATLAB software R2011a for implementing the DSP unit algorithms. The performance of each part of the system is analyzed by showing the optical spectrum, RF spectrum, electrical constellation diagrams, eye diagram and BER performance for different sampling rates and different bit rates.

Keywords: Coherent Reception, Digital Signal Processing, Optical Fiber Impairments.

1. Introduction

Physical impairments in the optical fiber, in particular, chromatic dispersion, fiber nonlinearities, polarization effects, and amplified spontaneous emission noise from the amplifiers, all interact, limiting the data rate and/or the transmission distances. Solutions for mitigating effects of these impairments are traditionally based on techniques in the optical domain, i.e., before the detection. The primary reason for this trend has been the background of researchers working in the field, who are mostly device physicists. Optical compensators, however, rely on adaptive optics and are usually slow in responding to the system degradation, and are expensive and bulky devices. Electrical domain approaches based on signal processing, on the other hand, offer great flexibility in design and can be integrated within the chip sets at the receiver, reducing bulkiness. Also, they can potentially operate after the optical signal has been partially demultiplexed so that electrical processing is done at a lower rate, hence substantially lowering the costs. The promise of signal processing approaches for optical communications has been noted more than a decade ago, but their successful demonstrations for high-speed optical communications have appeared more recently [1].

A significant effort has been expended in industry and academia to identify electronic signal processing as a cost-effective technique for upgrading data transmission to 10Gb/s for various applications over installed fibers. These applications include Local Area Networks (LAN), Storage Area Networks (SAN), metro-area networks, and long-haul

systems. The dominant installed fiber infra-structure for LAN and SAN is Multimode Fiber (MMF) and for metro and long-haul is Single-Mode Fiber (SMF). Such different installed media lead to very different engineering challenges due to different dispersion environments and introduce very different performance bounds. In addition to enabling upgrades to 10Gb/s over installed fiber, there is also current activity in the industry in using Plastic Optical Fiber (POF) with electronic signal processing as the most cost-effective and most power-efficient technique to enable 10-Gb/s transmission within data centers and smaller enterprises, as compared with 10GBASE-T over unshielded twisted copper pairs. Furthermore, there is also some effort on the use of electronic signal processing in 10Gb/s Ethernet Passive Optical Networks (10G EPON) for Access Networks [2].

The electronic signal-processing techniques can be broadly classified as adaptive equalization at the receiver, predistortion at the transmitter, and electric-field domain signal processing. The Electronic Dispersion Compensation (EDC) at the receiver can be most conveniently designed to be fully adaptive and, due to its ease of use and attractive economics, this approach will be emphasized [2].

In this context, Dual-Polarization Quadrature Phase-Shift Keying (DP-QPSK) transmission emerged as an attractive alternative. Such systems convey four bits per symbol (considering both polarization orientations), consequently reducing the symbol rate by the same factor in comparison to a binary system at the same bit rate. In addition to relaxing hardware requirements, the reduced

symbol rate also accounts for an increased tolerance to Inter-Symbol Interference (ISI). If coherently detected, polarization multiplexed QPSK signals can be separated at the receiver by signal processing algorithms, linear and nonlinear effects can be compensated using digital processing algorithms [3].

2. Channel Impairments Compensation

The symbiotic combination of Digital Signal Processing (DSP), coherent detection, and spectrally efficient modulation formats has resulted in the digital coherent optical receiver [4]. Coherent detection employing multilevel modulation format has become one of the most promising technologies for next generation high speed transmission system due to the high power and spectral efficiencies. With the powerful DSP, coherent optical receivers allow the significant equalization of chromatic dispersion (CD), polarization mode dispersion (PMD), phase noise (PN) and nonlinear effects in the electrical domain [5].

Because of the dynamic nature of some impairments such as PMD, compensators must be adaptive. Adaptation is not easily achieved in the optical domain because of the relative lack of flexibility in optical components, and because of the difficulty in extracting an appropriate error signal to control the adaptation. Adaptation that is required to track changing PMD conditions is relatively simple to implement electronically, with established adaptation algorithms such as the Constant Modulus Algorithm (CMA) and Least Mean Square (LMS) algorithm [6].

3. Coherent Detection

The most advanced detection method is coherent detection where the receiver computes decision variables based on the recovery of the full electric field, which contains both amplitude and phase information. Coherent detection thus allows the greatest flexibility in modulation formats, as information can be encoded in amplitude and phase, or alternatively in both in-phase (I) and quadrature (Q) components of a carrier. Coherent detection requires the receiver to have knowledge of the carrier phase, as the received signal is demodulated by a LO that serves as an absolute phase reference [7]. In direct detection as shown in Figure (1), in an opt electrical photo detector (a photodiode) the light intensity $|E|^2$ is converted in an electrical signal and the phase information is totally lost.

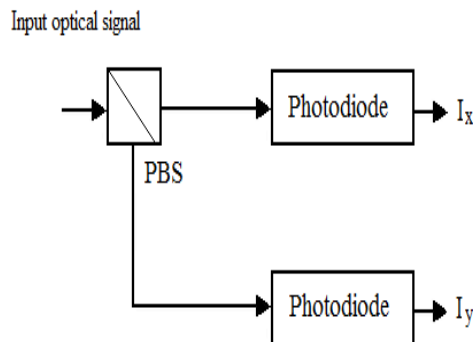


Figure 1. Schematic of direct receiver [8]

An alternative way to detect the optical signal is coherent detection in which the received signal is mixed with local laser being detected in the photodiode, and two detectors and proper phase delays are used, both amplitude and phase can be preserved as shown in Figure (2) [8].

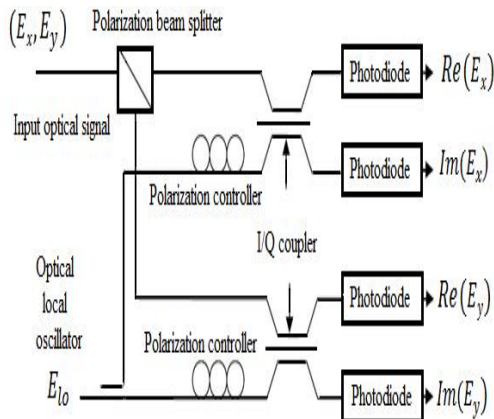


Figure 2. Schematic of coherent receiver [9]

While coherent detection was experimentally demonstrated as early as 1979, its use in commercial systems has been hindered by the additional complexity, due to the need to track the phase and the polarization of the incoming signal. In a digital coherent receiver these functions are implemented in the electrical domain leading to a dramatic reduction in complexity. Furthermore since coherent detection maps the entire optical field within the receiver bandwidth into the electrical domain it maximizes the efficacy of the signal processing. This allows impairments which have traditionally limited 40Gbit/s systems to be overcome, since both chromatic dispersion and polarization mode dispersion (PMD) may be compensated adaptively using linear digital filters [9].

4. Digital Signal Processing Aided Coherent Optical Detection

An important goal of a long-haul optical fiber system is to transmit the highest data throughput over the longest distance without signal regeneration. Digital signal processing (DSP) is used at the receiver to remove the need for dynamic polarization control and also to

compensate for linear (and some extent of non-linear) transmission impairments. An optical transmission system can be represented as shown in Figure (3).

where E_{TX} is the transmitted signal, $H(\omega)$ is the channel transfer function and E_{RX} is the received signal. The goal of DSP is to implement $H^{-1}(\omega)$, that can be interpreted as the combination of all the linear effects that affect the signal during the propagation, and estimate \hat{E}_{TX} that represents the processed signal. In order to compensate for all these effects, the received sampled electrical signal is elaborated with a series of algorithms in order to minimize the bit error rate (BER) that represents the main evaluation criterion for digital communication system quality [10].

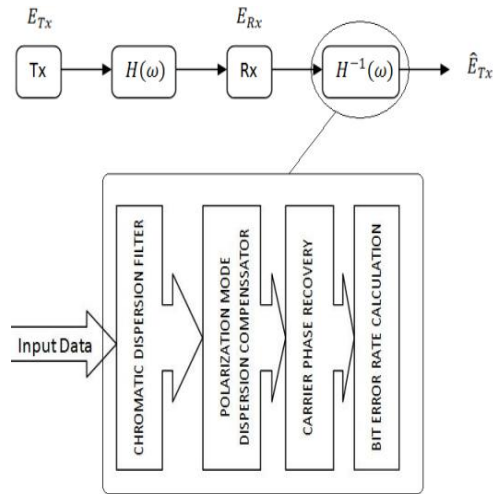


Figure 3. Transmission and DSP block scheme [10]

5. Dual-Polarization Quadrature Phase Shift Keying System Design

System setup is established using OPTISYSTEM(2011) and MATLAB(2011) as shown in Figure (4).

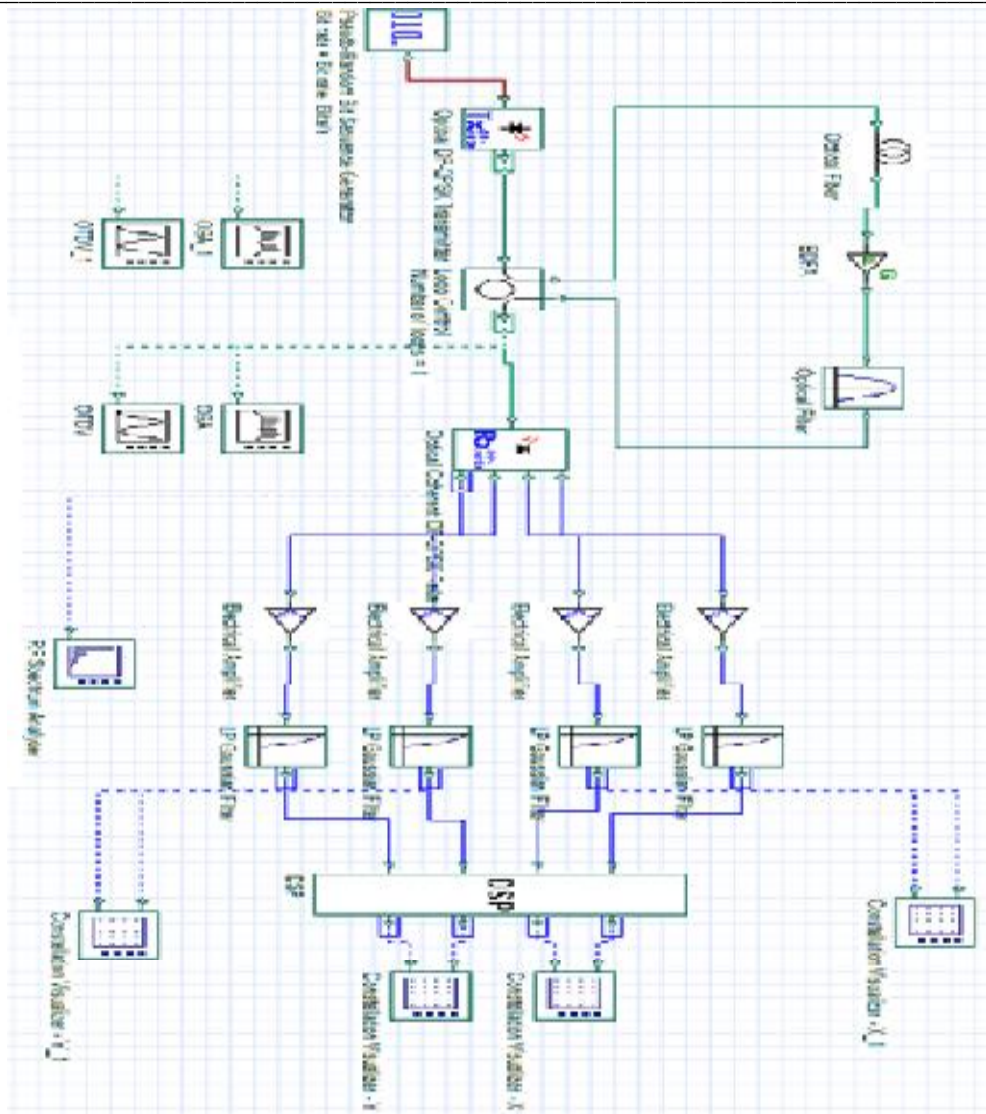


Figure 4. DP-QPSK Coherent System with DSP

The system can be divided into five main parts: DP-QPSK Transmitter, Transmission Link, Coherent Receiver, Digital Signal Processing, and Detection & Decoding (which is followed by direct-error counting). The signal is generated by an optical DP-QPSK Transmitter then propagated through the fiber loop where dispersion and polarization effects occur. The layout representing the optical coherent dual-polarization QPSK

transmitter for a single channel transmission component is shown in Figure (5). In this case, polarization multiplexing is used, the laser output is split into two orthogonal polarization components by Polarization Beam Splitter (PBS), which are modulated separately by QPSK modulators and then combined using a Polarization Beam Combiner (PBC).

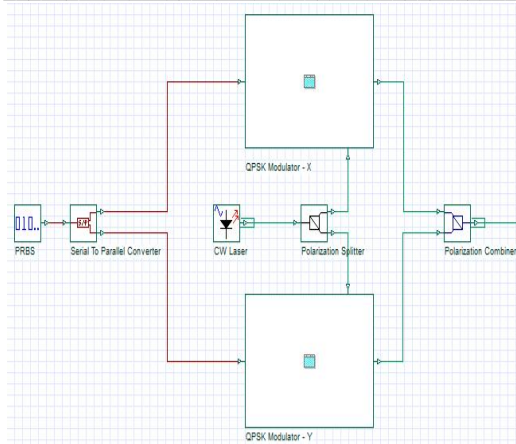


Figure 5. Optical dual-polarization QPSK transmitter equivalent layout

For this model, 40Gb/s Pseudo Random Bit Sequence (PRBS) generator is modulated into two orthogonally polarized QPSK optical signals by two QPSK modulators, Bit rate is 40 Gb/s, Sample rate is 1.28×10^{12} Hz, Input signal power is 10 dBm and Wavelength is 1550 nm. Figure (6) represents a QPSK Modulator which starts with the PSK Sequence Generator to Generate two parallel M-ary symbol sequences from binary signals using phase shift keying modulation (PSK) (with 2 Bits per symbol).

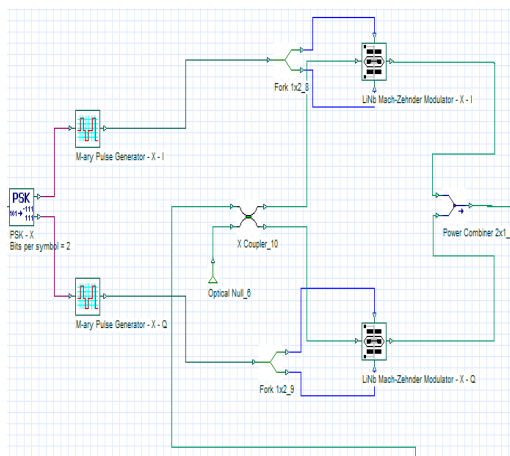


Figure 6. QPSK Modulator

After that, it passes through M-ary Pulse Generator to Generates multilevel pulses according to the M-ary signal input (with 1 bit Duty cycle), then each signal is modulated by Lithium Niobate Mach-Zehnder Modulator and combined together to form the QPSK signal.

The transmission link as shown in Figure (7) is composed of 2 fiber spans. Each span contains SSMF with length = 50 km. The optical fiber component simulates the propagation of an optical field in a single-mode fiber with the dispersive and nonlinear effects taken into account by a direct numerical integration of the modified Nonlinear Schrödinger (NLS) equation (when the scalar case is considered) and a system of two, coupled NLS equations when the polarization state of the signal is arbitrary.

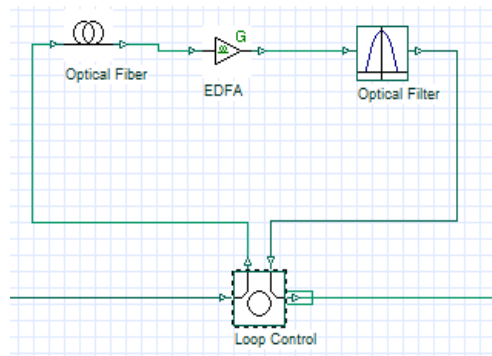


Figure 7. Transmission link

The optical coherent dual-polarization QPSK receiver consists of a homodyne receiver design. The component has a Local Oscillator (LO) laser polarized at 45 degrees relative to the polarization beam splitter, and the received signal is separately demodulated by each LO component using two single polarization QPSK receivers. Figure (8) shows the layout representing the receiver.

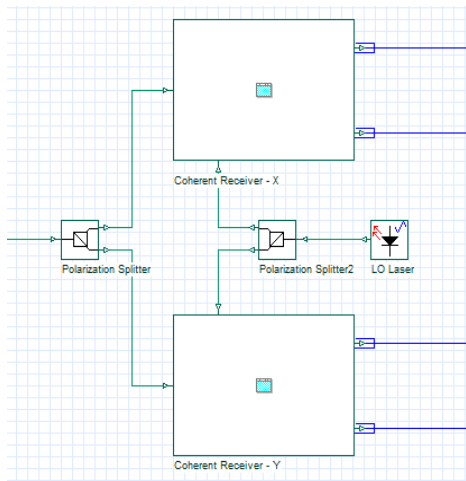


Figure 8. Optical Coherent DP-QPSK Receiver

The optical coherent QPSK receiver consists of a homodyne receiver design. In a homodyne receiver, the frequency of the Local Oscillator (LO) laser is tuned to that of the TX laser so the photo receiver output is at baseband. The component is formed by a set of 3 dB fiber couplers, a LO laser, and balanced detection. Figure (9) shows the layout representing the receiver.

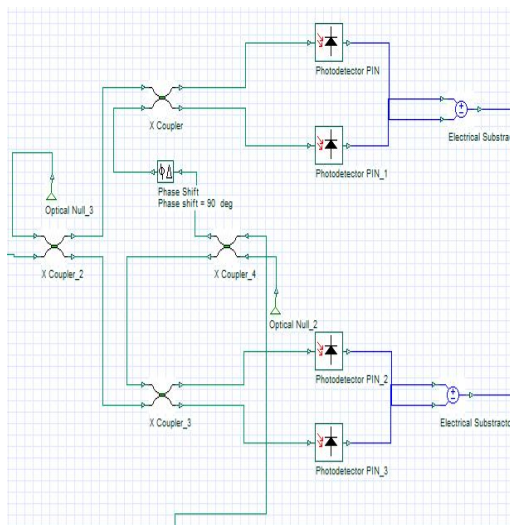


Figure 9. QPSK Receiver

The four output signals from Optical Coherent DP-QPSK Receiver are I and Q of the two polarizations (X, Y), which have the full information of transmitted signal. These received electrical signals are then amplified with a set of four electrical amplifiers having a gain of 15 dB each as shown in Figure (10). After amplification, the signals are passed through Low Pass Gaussian filters to eliminate the frequencies above the required band.

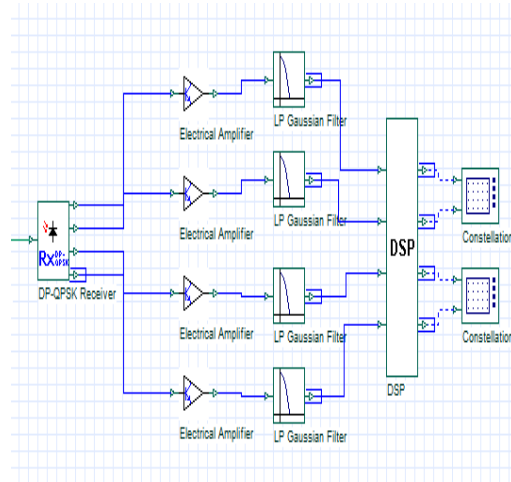


Figure 10. Amplification and filtering of the received signals

6. Digital Signal Processing (DSP) Unit

After the four signals are amplified and filtered, they are passed to the DSP unit for channel impairments compensation as shown in Figure (10). The algorithms used for digital signal processing are implemented through a MATLAB component. The inner structure of the DSP modules is shown in Figure (11).

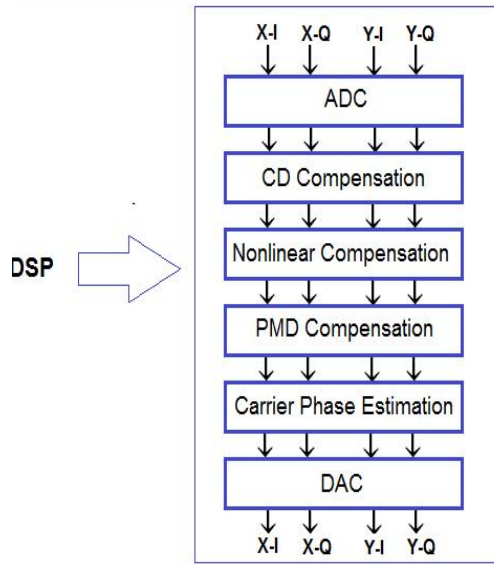


Figure 11. DSP Structure

The four signals enter the DSP first they are converted to digital domain for processing then the fiber dispersion is compensated using a simple transversal digital filter followed by a butterfly Nonlinear Compensator structure (NLC) to compensate the nonlinear effects and the adaptive PMD compensation is realized by applying the Constant-Modulus Algorithm (CMA). A modified Viterbi-and-Viterbi phase estimation algorithm (working jointly on both polarizations) is then used to compensate for phase and frequency mismatch between the transmitter and local oscillator (LO).

a) Analog to Digital Conversion

The analog to digital conversion is basically a down sampling process. A 2-bit sampling is chosen, however sampling rate can be changed.

b) CD Compensation

In the absence of fiber nonlinearity, the fiber optic can be modeled as a filter with the transfer function as given in Equation (1).

$$G(z, \omega) = e^{-j\frac{D\lambda^2}{4\pi c}\omega^2 z} \quad (1)$$

In order to compensate the Chromatic Dispersion simple transversal digital filter is used , we multiply the output field by the inverse of the channel transfer function (FIR filter).The magnitude response for this filter is shown in Figure (12).The order of the filter increases as the amount of dispersion (length of the propagation) increases.

c) Nonlinear Effects Compensation

For the presented system single channel transmission is used so the nonlinear impairments effect is limited to SPM. SPM affects the phase of signals and causes spectral broadening, which in turn leads to increases in dispersion penalties. SPM compensation is done by nonlinear compensator (NLC) as shown in Figure (13) based on the technique of multi-span back-propagation.

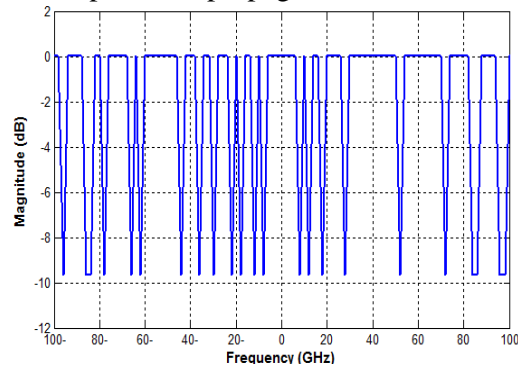


Figure 12. The magnitude response of CD compensating filter

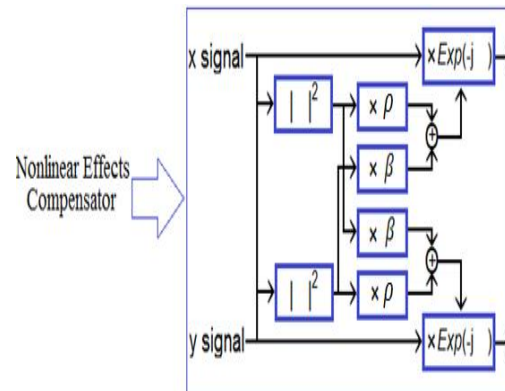


Figure 13. (NLC) Compensator

$$E_x^{out} = E_x^{in} e^{-j(\rho I_x + \beta I_y)} \quad (2)$$

$$E_y^{out} = E_y^{in} e^{-j(\rho I_x + \beta I_y)} \quad (3)$$

Where $I_x = |E_x|^2$, $I_y = |E_y|^2$, ρ is the intra-polarization nonlinearity parameter and β is the inter-polarization nonlinearity parameter and has to be optimized. The best BER was found for ρ and $\beta = 25$.

d) PMD Compensation

The Jones matrix of the fiber for transmission can be written as

$$T = \begin{bmatrix} \sqrt{\sigma} e^{i\delta} & -\sqrt{1-\sigma} \\ \sqrt{1-\sigma} & \sqrt{\sigma} e^{-i\delta} \end{bmatrix} \quad (4)$$

where σ and δ denote the power splitting ratio and the phase difference between the two polarization modes. The State Of Polarization (SOP) of the output signal can be written as:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = T \begin{bmatrix} E_{in,x} \\ E_{in,y} \end{bmatrix} \quad (5)$$

By knowing the inverse of matrix T, we can do polarization de-multiplexing. The CMA is a conventional way for this. Figure (14) shows the DSP circuit for channel expression. The h matrix is basically an adaptive FIR filter. CMA is used for blind estimation. For the proposed system a 3-tap FIR filter is chosen, however the order can be changed. The initial values are:

$$\begin{aligned} h_{xx} &= (... 010 ...), \\ h_{yx} &= (... 000 ...), \\ h_{xy} &= (... 000 ...), \\ h_{yy} &= (... 010 ...). \end{aligned}$$

e) Carrier Phase Estimation(CPE)

Phase locking in the hardware domain can be replaced by phase estimation in digital domain by DSP. The received

QPSK signal can be presented by Equation (6).

$$E(t) = A \exp\{j[\theta_s(t) + \theta_c(t)]\} \quad (6)$$

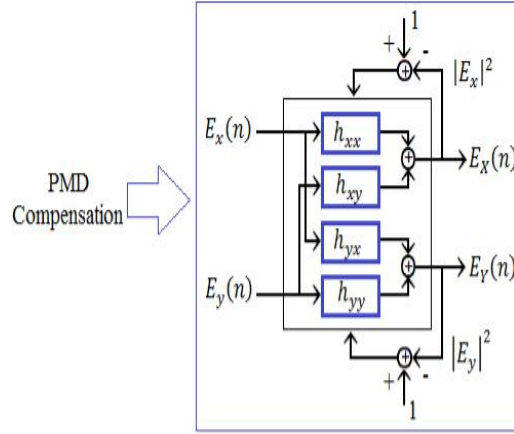


Figure 14. PMD Compensation

During this step frequency and phase offset between local oscillator and signal is compensated using "Viterby-and-Viterby" method (working jointly on both polarizations) as explained in Figure (15).

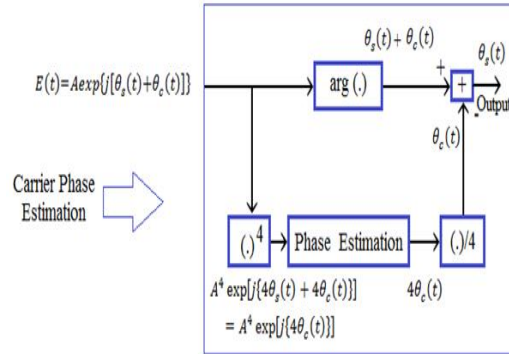


Figure 15. Carrier Phase Estimation

After the digital signal processing is completed, the signal is sent to the detector and decoder, and then to the BER test set for error detection as shown in Figure (16).

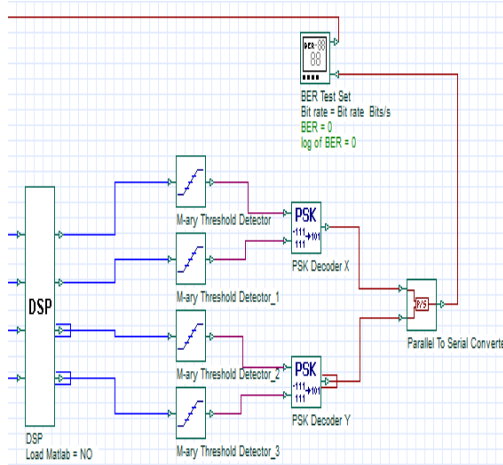
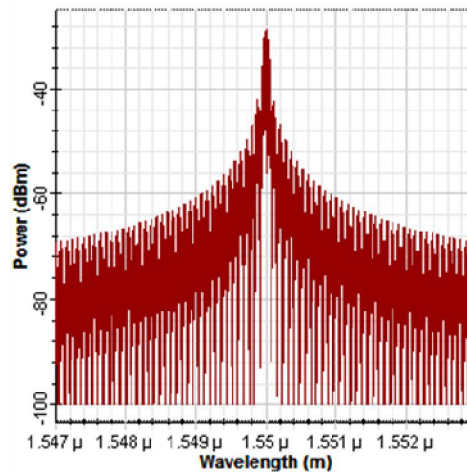


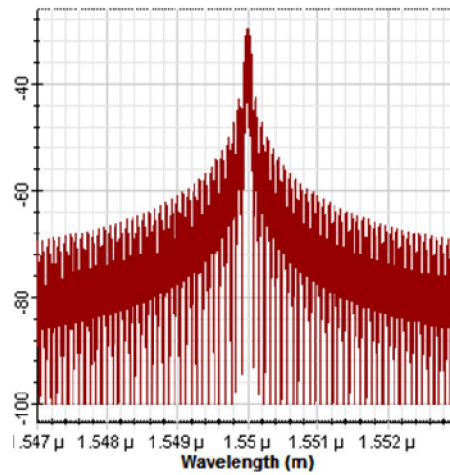
Figure 16. Detecting and Decoding after the DSP

7. Performance of 40 Gb/s (DP-QPSK) Coherent System with DSP

Figure (17) shows the optical power spectrum of the transmitted QPSK signals in polarizations(X,Y) in (a) and (b) respectively that will be transmitted through the optical fiber. Figure (18) shows the optical power spectrum of the transmitted QPSK signals with optical power spectrum of the noise (the green signal) added after it has passed through the transmission optical channel. Figures (19) shows RF Spectrum of the (DP-QPSK) receiver's output signals for X,Y-polarizations. Figure (20) displays the In-Phase and Quadrature-Phase of electrical signals for X,Y polarizations in a constellation diagram after it passes through the Electrical Amplifiers and Low Pass Gaussian Filters. Figure (21) displays the In-Phase and Quadrature-Phase of electrical signals for X,Y polarizations in a constellation diagram after it passes through the DSP unit.

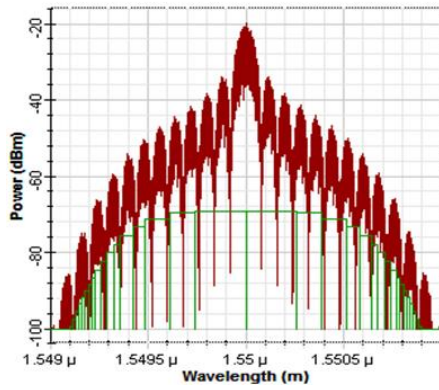


(a)

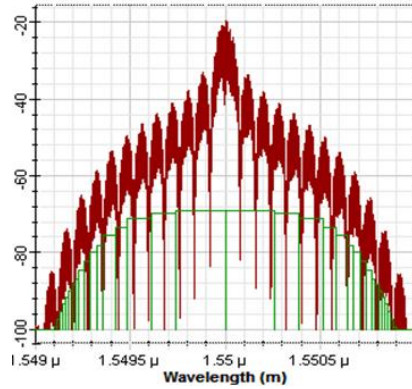


(b)

Figure 17. Optical power spectrum of the transmitted QPSK signals.(a) X-Polarization, (b) Y-Polarization.

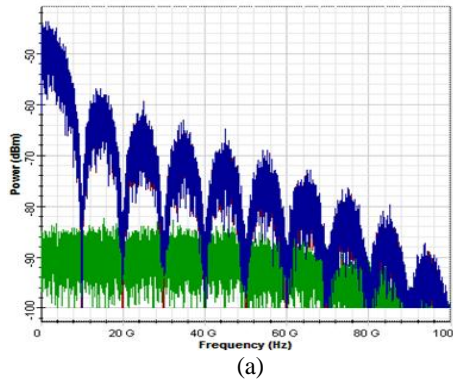


(a)

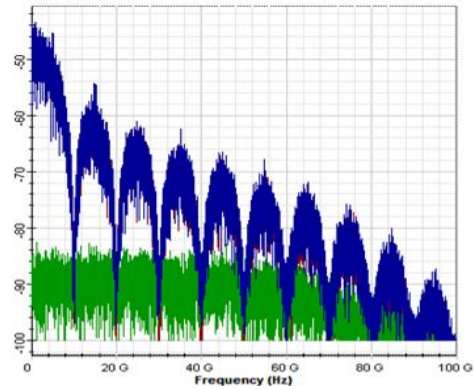


(b)

Figure 18. Optical power spectrum of the QPSK signals after the transmission channel. (a) X-Polarization, (b) Y-Polarization.

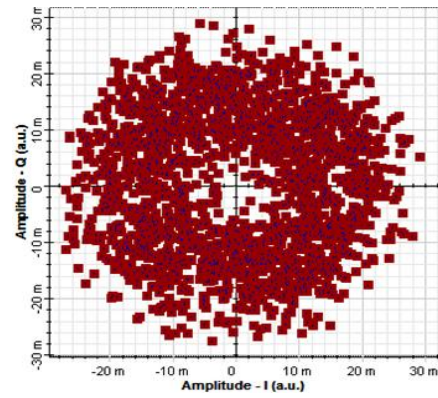


(a)

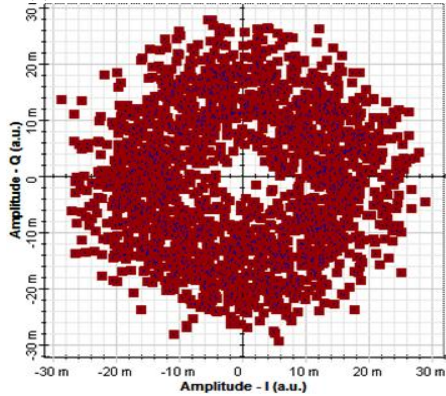


(b)

Figure 19. RF Spectrum of the (DP-QPSK) receiver's output signals. (a)X-Polarization, (b) Y-Polarization.



(a)



(b)

Figure 20. I-Phase and Q-Phase of electrical signals. (a)X-polarization, (b) Y-polarization.

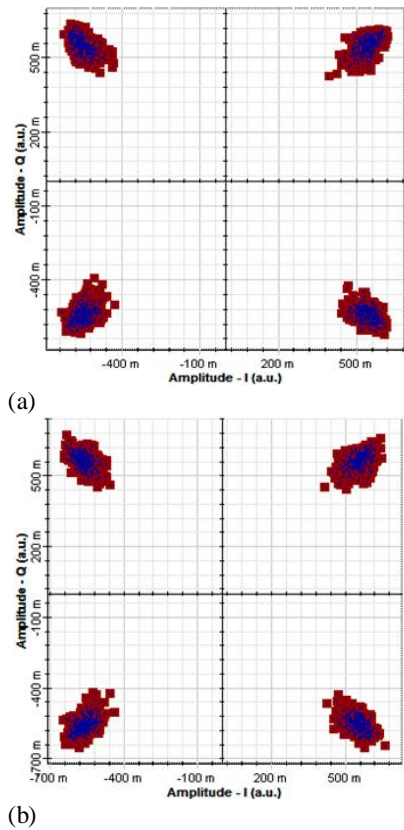


Figure 21. The In-Phase and Quadrature-Phase of electrical signals.(a) X-polarization,(b) Y-polarization

8. Performance of the DSP Unit

The algorithms used for digital signal processing are implemented through a Matlab component. By setting the Matlab component to debug mode, the generated electrical constellation diagrams before DSP shown in figure (22).Figure (23) shows electrical constellation diagrams for both signals (X,Y) polarizations after CD compensation .Figure (24) shows electrical constellation diagrams for both signals (X,Y) polarizations after Nonlinear Effects Compensation .Figure (25) shows electrical constellation diagrams for both signals (X,Y) polarizations after PMD compensation .Figure (26) shows electrical constellation diagrams for both signals

(X,Y) polarizations after Carrier Phase Estimation .

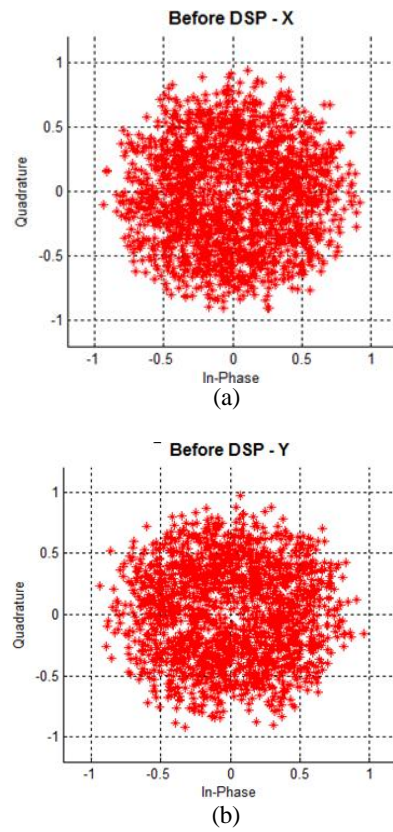
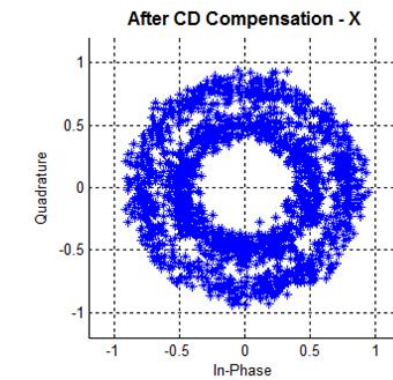
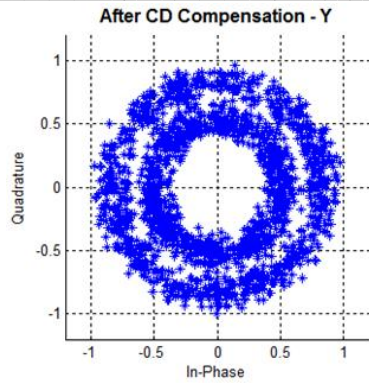


Figure22. Electrical constellation diagrams before the DSP.(a) X-polarization,(b) Y-polarization.

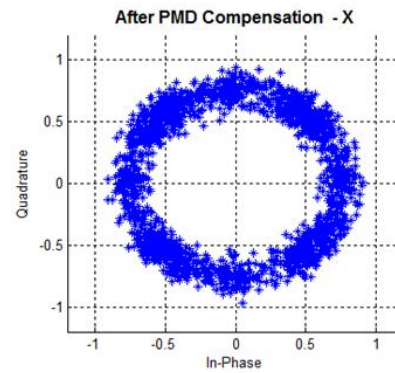


(a)

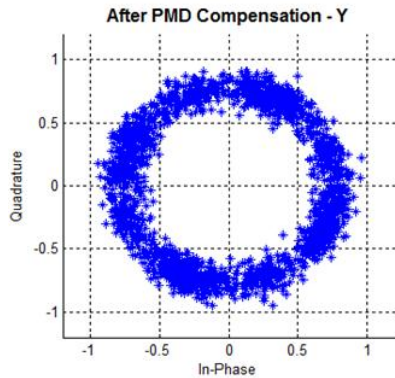


(b)

Figure 23. Electrical constellation diagrams after CD compensation. (a) X-polarization, (b) Y-polarization.

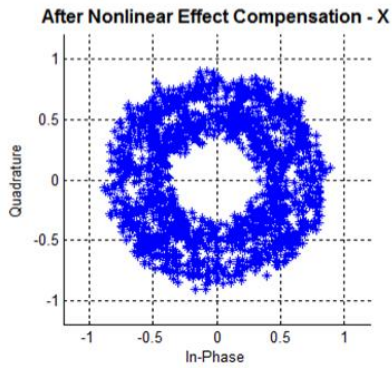


(a)

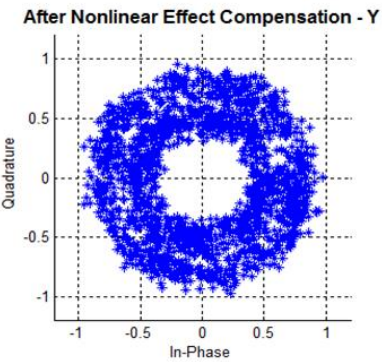


(b)

Figure 25. Electrical constellation diagrams after PMD compensation. (a) X-polarization, (b) Y-polarization.

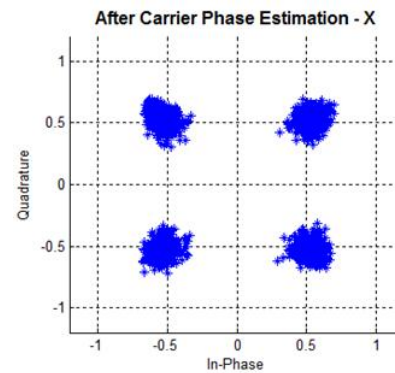


(a)

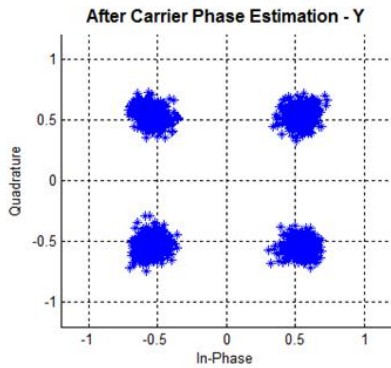


(b)

Figure 24. Electrical constellation diagrams after Nonlinear Effects Compensation. (a) X-polarization, (b) Y-polarization.



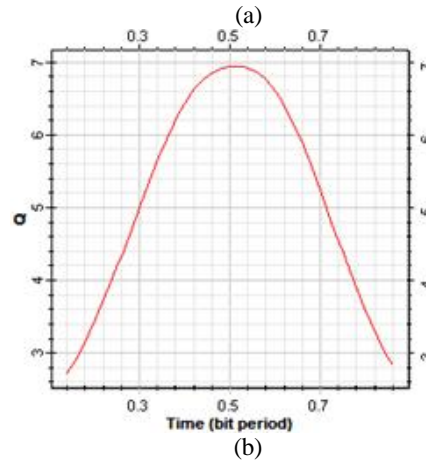
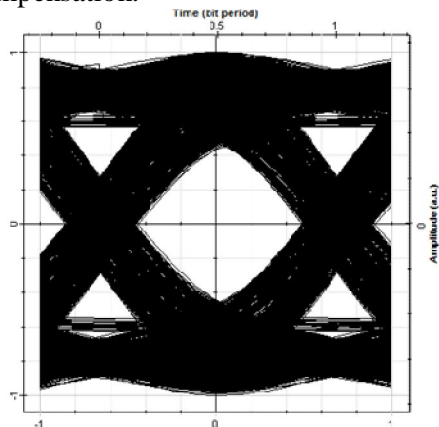
(a)



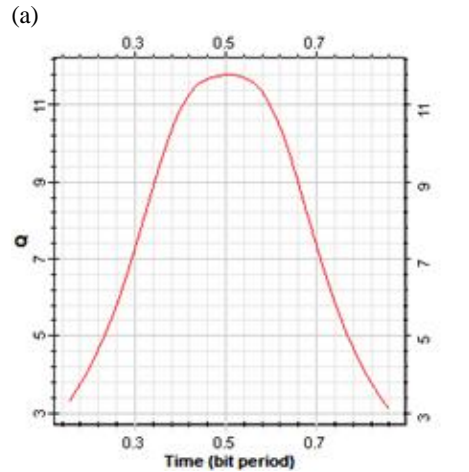
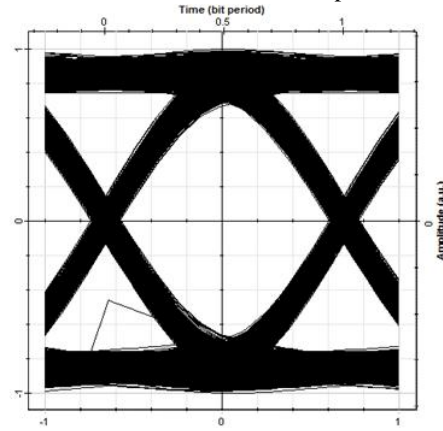
(b)
Figure 26. Electrical constellation diagrams after Carrier Phase Estimation.(a) X-polarization,(b) Y-polarization.

9. Eye Diagrams

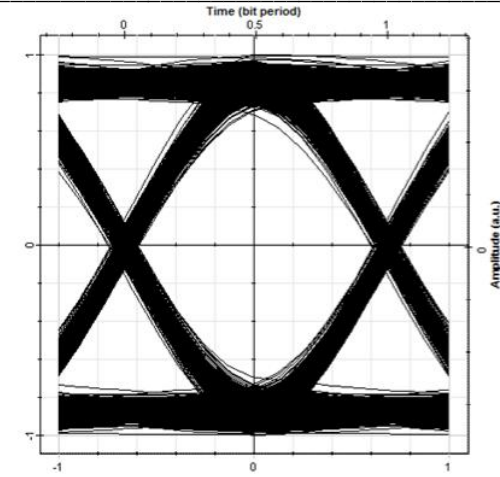
The generated eye diagrams after each step of the DSP obtained using (OptiSystem2011) are shown in the figures (27-30). Figure (27) in (a) and (b) show the eye diagram and Q factor respectively for the X-polarization OPSK signal before CD, PMD and Nonlinear effect compensations. Figure (28) in (a) and (b) show the eye diagram and Q factor respectively for the X-polarization OPSK signal after CD compensation. Figures (29) in (a) and (b) show the eye diagram and Q factor respectively for the X-polarization OPSK signal after PMD compensation. Figure (30) in (a) and (b) show the eye diagram and Q factor respectively for the X-polarization OPSK signal after Nonlinear effects compensation.



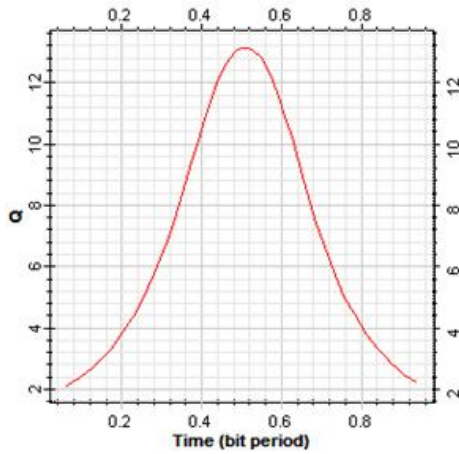
(b)
Figure 27. Eye diagram and Q factor before CD, PMD, Nonlinear effect compensations.



(b)
Figure 28. Eye diagram and Q factor for X-polarization after CD Compensation.

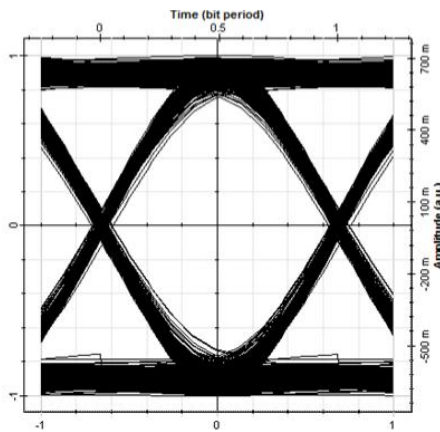


(a)

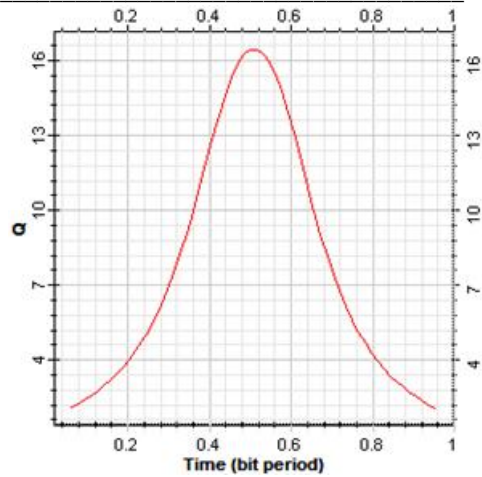


(b)

Figure 29. Eye diagram and Q factor for X-polarization after PMD Compensation.



(a)



(b)

Figure 30. Eye diagram and Q Factor for X-polarization after Nonlinear Effects compensation.

10. Analysis of BER Performance

Figure (31) represents the BER performance with Optical Signal to Noise Ratio (OSNR) (DP-QPSK) Coherent optical system for two sampling rates 2 and 4 samples per symbol. According to the results the system performance shows an obvious improvement with the increment of the sampling rate. Figure (32) represents the BER performance with OSNR for two bit rate 40 Gb/s and 100 Gb/s. The simulation result shows that 40 Gb/s system has better performance than 100 Gb/s.

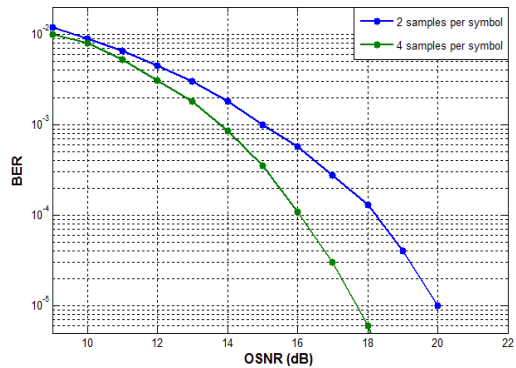


Figure 31. BER performance with OSNR for different sampling rates

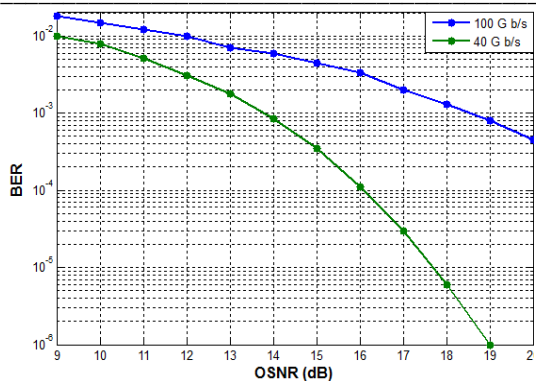


Figure 32. BER performance with OSNR for different bit rates.

11. Conclusions

- 1.40 Gb/s (DP-QPSK) Coherent system with DSP unit is designed using OptiSystem(2011) interfaced with MATLAB R2011a for implementing the DSP unit algorithms. The performance of each part of the system is analyzed by showing the optical spectrum, RF spectrum and electrical constellation diagrams for the transmitted signals with noise signals in both polarizations (X,Y)
2. The performance of the DSP unit for optical impairments compensation is analyzed by electrical constellation diagrams, Eye diagrams with Q factor after each step (CD compensation, Nonlinear effect compensation, PMD compensation and Carrier Phase Estimation) are presented. It was found from constellation diagram that adding DSP unit improves the system performance drastically by clearly distinguishing the constellation points at the desired bit positions.
3. The BER performance with Optical Signal to Noise Ratio (OSNR) of (DP-QPSK) Coherent optical system for two sampling rates 2 and 4 samples per symbol is analyzed. The

system performance shows an obvious improvement with the increment of the sampling rate. BER performance with OSNR for two bit rate 40 Gb/s and 100 Gb/s is presented, the simulation result shows that 40 G b/s system has better performance than 100 Gb/s.

References

- [1] T. Adair, W. Wang, and A. O. Lima, "Electronic Equalization in Optical Fiber Communications", IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Vol. IV, pp. 497-500, 2003.
- [2] I. P. Kaminow, T. Li, A. E. Willner, "Optical Fiber Telecommunications V A Components and Subsystems", Elsevier Science, (USA), 2008.
- [3] T. F. Portela, D. V. Souto, V. N. Rozental, H. B. Ferreira, D. A. A. Mello, "Analysis of Signal Processing Techniques for Optical 112 Gb/s DP-QPSK Receivers with Experimental Data", Journal of Microwaves, Optoelectronics and Electromagnetic Applications, Vol. 10, No. 1, June 2011.
- [4] S. J. Savory, "Digital Coherent Optical Receivers: Algorithms and Subsystems", IEEE Journal of Selected Topics in Quantum Electronics, Vol. 16, No. 5, pp. 1164-1179, October, 2010.
- [5] T. Xu, "Digital Dispersion Equalization and Carrier Phase Estimation in 112-Gbit/s Coherent Optical Fiber Transmission System", Licentiate Thesis, Royal Institute of Technology, Stockholm, Sweden, 2011.
- [6] J. Sewter, "Electronic Equalization of Polarization Mode Dispersion in 40 G b/s Optical Systems", MSc. Thesis, Electrical and Computer Engineering, University of Toronto, 2005.
- [7] E. Ip, "Coherent Detection and Digital Signal Processing for Fiber Optic Communications", PhD. Thesis, Department of Electrical Engineering, Stanford University, December, 2008.
- [8] M. Mussolin, "Digital Signal Processing Algorithms for High-Speed Coherent Transmission in Optical Fibers", M Sc. Thesis, Telecommunications Engineering, Padova University, Italy, 2010.
- [9] S. J. Savory, "Digital Filters for Coherent Optical Receivers", Optical Society of America, Optical Express, Vol. 16, No.2, pp. 804-816, 2008.
- [10] S. J. Savory, G. Gavioli, R. I. Killey, P. Bayvel, "Electronic compensation of chromatic dispersion using a digital coherent receiver", Optical Society of America, Optical Express, Vol. 15, No. 5, pp. 2120-2126, 2007.