STUDY OF TRANSMISSION IMPAIRMENTS IN HIGH SPEED OPTICAL COMMUNICATION SYSTEMS

A project Report

Submitted by

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In partial fulfillment of the requirements

For the award of the degree of

MASTER OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS

JUNE 2013

THESIS CERTIFICATE

This is to certify that the thesis entitled "**STUDY OF TRANSMISSION IMPAIRMENTS IN HIGH SPEED OPTICAL COMMUNICATION SYSTEMS"** submitted by **RAJAMADASAMY.M** to the Indian Institute of Technology, Madras for the award of the degree of Master of Technology is a bonafide record of research work carried out by him under my supervision. The contents of this thesis, in full or part, have not been submitted to any other Institute or University for the award of any degree or diploma.

Chennai – 600036

Research Guide

(Dr. Deepa Venkitesh)

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my guide Dr. Deepa Venkitesh for her guidance and constant encouragement throughout the project work. I am grateful to her for providing me for her valuable time to discuss the issues related to project work

I extend my gratitude to research scholars Sanjay, Saikrishna and Aravind for their everlasting support.

ABSTRACT

With internet traffic growing exponentially in recent years, there is an increasing demand for reliable high capacity long haul optical communication links. One of the ways to increase the per fiber link capacity in the existing is to use higher modulation techniques that provides higher spectral efficiency.

In this thesis, we will discuss and compare the performance of different modulation formats in high speed optical communication systems. Benefits of encoding the information into phase of the optical carrier are discussed. Performance of modulation formats over existing transmission fibers networks are compared in 10 Gbps and 40 Gbps data rate systems.

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LIST OF ACRONYMS

ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
CD	Chromatic Dispersion
DCF	Dispersion Compensated Fiber
DPSK	Differential Phase Shift Keying
FWM	Four Wave Mixing
GVD	Group Velocity Dispersion
ISI	Inter-Symbol Interference
MZI	Mach Zehnder Interferometer
NRZ	Non-Return to Zero
OOK	On-Off Keying
OSNR	Optical Signal to Noise Ratio
PMD	Polarisation Mode Dispersion
PRBS	Pseudo Random Binary Sequence
PSK	Phase Shift Keying
RZ	Return to Zero
SMF	Single Mode Fiber
SPM	Self Phase Modulation
TDM	Time Division Multiplexing
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

CHAPTER I

Introduction

1.1 Light wave Communication Systems

Since the introduction of fiber optic communication system in early eighties, demand for increasing the network has been met by increasing the data rate of single channel and by use of wavelength division multiplexing (WDM) systems. Till today predominantly used modulation format is intensity modulation with direct detection, also known as On-Off Keying (OOK). Inter-Symbol Interference (ISI) caused due to chromatic dispersion (CD) and polarisation mode dispersion (PMD) increases with baud rate and severely degrades the signal quality as it propagates through for long distance thereby limiting the higher bit rate for TDM systems [1].

Various digital signal processing techniques have been introduced to increase the dispersion tolerance at 10 Gbps [2][3]. The cost effective way of increasing the network capacity of the existing fiber links together with reduction of cost per transported bit remains a challenging task.

In WDM systems, cost reduction is achieved by sharing of optical components among the different wavelength channels. Since all the shared components operated within the limited wavelength windows, these channels have to be packed as close as possible to get higher per channel spectral efficiency .i.e. number of information bits transmitted per Hz of the bandwidth

One of the ways to increase the spectral efficiency is increasing the per channel data rate. Today's advancements in high speed electronics not only helped to push channel rates but also provide sophistication in optical transponders. Hence systems starts coming up which no longer relied only on the binary level intensity modulation, and begin to use multilevel phase modulation formats [4].

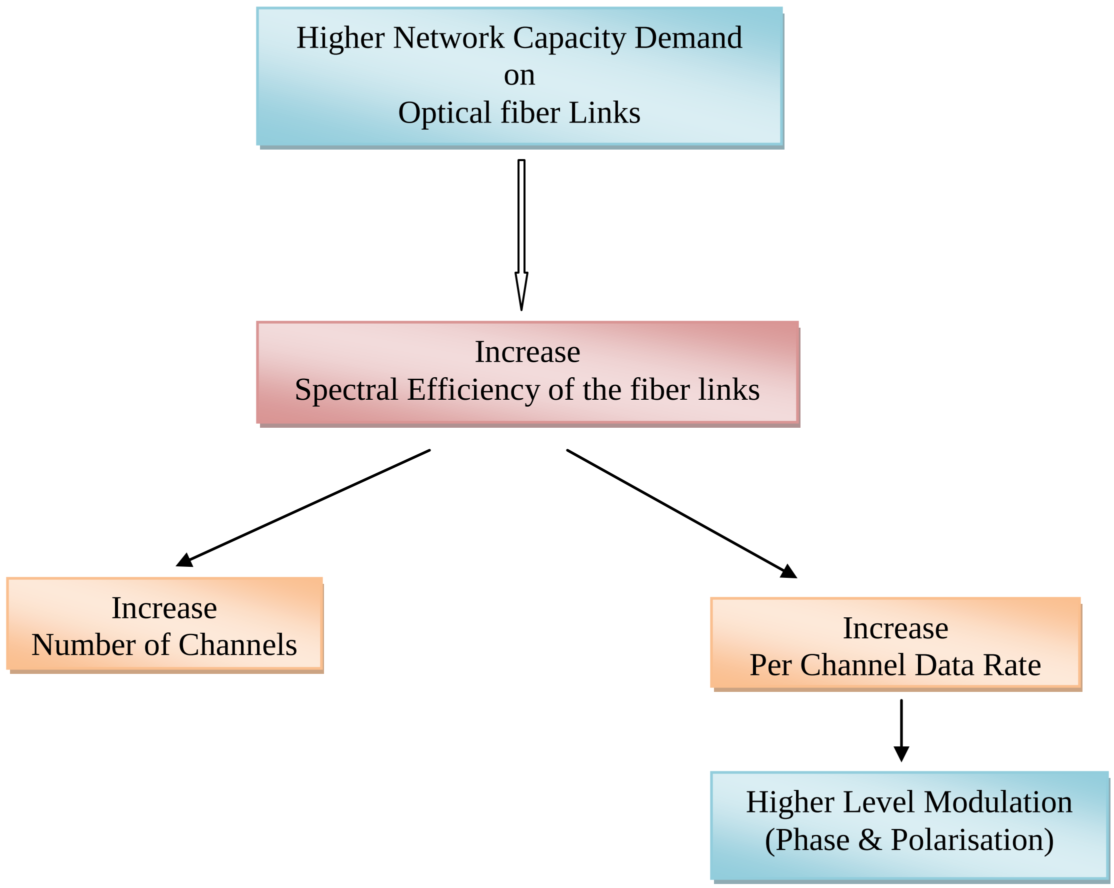

Figure 1.1 Need for Advanced Modulation Formats

Flowchart in the Figure 1.1 summaries the ways on how to meet higher demand for capacity addition in the existing fiber links which are already deployed commercially. To attain this we have increase the spectral efficiency of the transport links i.e. higher number of bits per second per usable bandwidth. This can be done either by increasing the number of channels in the WDM systems or by increasing the per channel data rate of WDM systems so that overall capacity is increased. The latter can be done by employing higher level of modulation formats such as encoding the data into phase and/or polarisation of the optical carrier signal.

1.2 Advanced Modulation Formats

Higher Bandwidth-Distance product, key figure of merit for light wave communication systems, can be achieved by increasing the per channel data-rate and by reducing the channel spacing between in the DWDM systems. But in these high speed WDM systems linear and nonlinear distortions on the optical signal become worse. These linear impairments include chromatic dispersion (CD) and polarization mode dispersion (PMD); nonlinear impairments include self phase modulation (SPM), cross phase modulation (XPM) and four-wave mixing (FWM).

To minimize both the linear and the nonlinear impairments over the transmission fiber, an optimal modulation format is needed. A modulation format with a narrow optical spectrum can enhance spectral efficiency and tolerate more CD distortion. A modulation format with constant optical power can be less susceptible to SPM and XPM; Modulation format with multiple signal levels will carry more information than binary signals and its longer symbol duration will reduce the distortion induced by CD and PMD. In addition to that modulation format which is tolerant to ASE noise is desirable in long haul networks [5] [6].

1.3 Impairments due to Dispersion

An optical signal gets distorted when it travels along the fiber, a weakly guiding dielectric waveguide. The dispersion effect causes different delay to each of the optical signal's frequency components, so that, at the detector, these components arrive at different times. All this produces a distorted signal with respect to the transmitted one. This phenomenon is illustrated in the Figure 1.2 shown below, where each pulse broadens and overlaps with its neighbours and thus becoming indistinguishable at the receiver.

In the single mode fibers, which are predominantly used in the communication links, dispersion is caused by chromatic or material dispersion and waveguide dispersion. Polarisation mode dispersion which manifests itself at higher bit rate systems is caused due fiber birefringence. Chromatic dispersion arises due to fact that different spectral components of the pulse signal travel at slightly different group velocities, a phenomenon commonly referred as Group Velocity Dispersion (GVD)

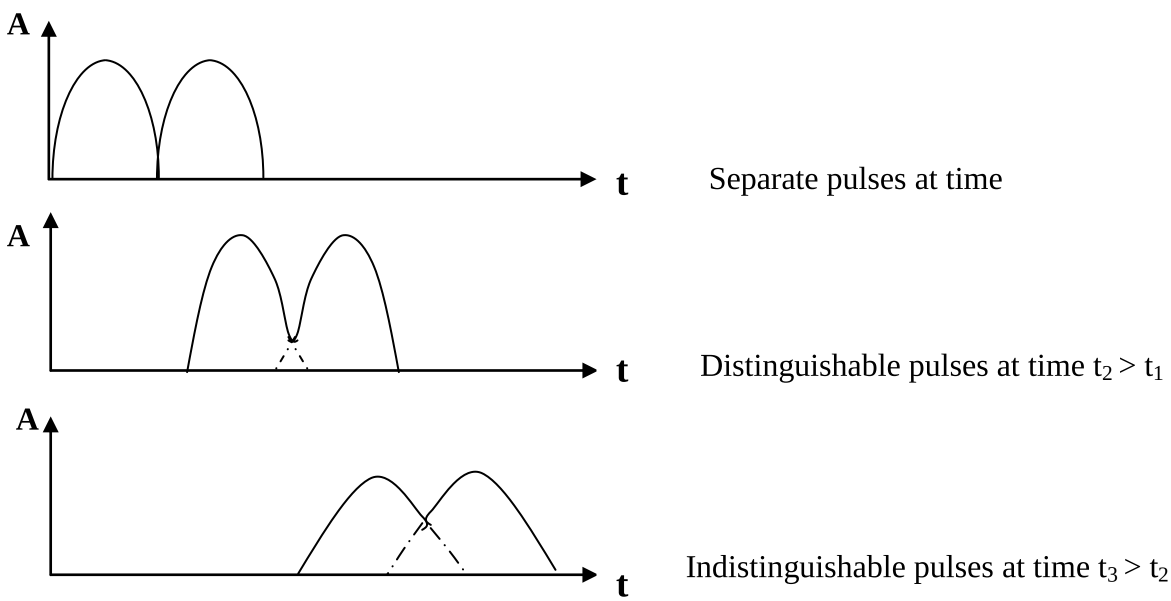

Figure 1.2 Illustration of pulse broadening in the time domain

1.4 Impairments due to Nonlinearity

Although material used for making optical fibers, silica glass has very small nonlinear coefficients, the nonlinear effects in optical fibers are generally not negligible. When the optical intensity of a propagating signal is very high, it gets distorted by significant effects of nonlinearity. The nonlinear effects can be divided into two cases based on their origins: stimulated scatterings and optical Kerr effects.

Kerr effect is the result of intensity dependence of the refractive index of an optical fiber leading to a phase constant that is a function of the optical intensity. There are two inelastic stimulated scattering phenomena in an optical fiber: Raman scattering and Brillouin scattering. The intensity dependence of refractive index results in self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). Inelastic stimulated scatterings are associated with threshold powers at which their effects become significant.

CHAPTER II

Split Step Fourier Method

In this chapter we discuss about the Nonlinear Schrodinger (NLS) equation that characteristics the propagation of optical pulse through the fiber. Split-step Fourier transform technique is used to simulate the pulse propagation characteristics inside the fiber.

2.1 Nonlinear Schrodinger Equation(NLSE)

Evolution of a pulse propagating through a single mode fiber is characterized by an equation called Nonlinear Schrodinger equation (NLS), and is given by

$$i\frac{\partial A}{\partial z}+\frac{i\alpha}{2}A+\frac{D\lambda^2}{4\pi c}\frac{\partial^2 A}{\partial T^2}+\gamma\left|A\right|^2 A=0 \quad ....(1)$$

Where, A is envelope of the pulse propagating through the fiber

T is the time in a frame of reference moving with the envelope i.e T = $t-\frac{\beta_1 z}{v_g}$

λ is the wavelength of the light.

c is the velocity of light in free space

z is the distance along the length of the fiber

v_g is the group velocity of the wave

β_1 is the propagation constant

The NLS equation is a nonlinear partial differential equation that does not generally have analytic solutions except under certain conditions. It can be solved numerically using different methods to give the evolution of pulse as it propagates through the optical fiber. One of the method used to simulate is Split Step Fourier Transform method a pseudo spectral method which is order of magnitude faster than finite difference methods for same accuracy. .

2.2 Split Step Fourier Method

Generalised NLS equation is rewritten in the following form as

$$\frac{\partial A}{\partial z} = \left(\hat{D} + \hat{N}\right)A \qquad \text{-- 2.2}$$

where $\hat{D}$ is a differential operator that accounts for dispersion and losses within a linear medium and $\hat{N}$ is a nonlinear operator that governs the effect of fiber nonlinearities on pulse propagation. [6]. These operators are given by

$$\hat{D} = \frac{i\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial T^3} - \frac{\alpha}{2} \qquad \text{--- 2.3}$$

$$\hat{N} = i\gamma(|A|^2 + \frac{i}{\omega_0}\frac{1}{A}\frac{\partial}{\partial T}(|A|^2 A) - T_R\frac{\partial |A|^2}{\partial T}) \qquad \text{--- 2.4}$$

Exact solution for equation 2.2 is given as follows

$$A(z+h,T) = exp[h(\hat{D} + \hat{N})]A(z,T),$$

In this method, the entire length of the fiber is split into number of subsections of smaller lengths and in each subsection the NLS equation is solved separately in frequency domain. Finally all these solutions are added to give the final pulse shape.

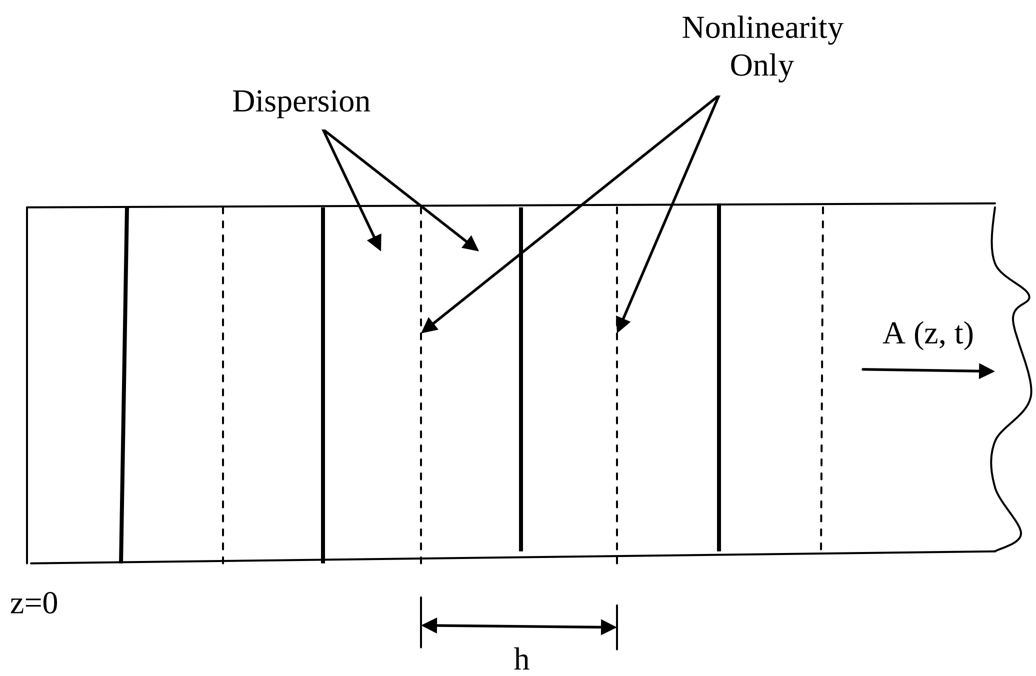

Figure 2.1 Schematic illustration of the symmetrical SSFT method [6].

As shown in the Figure 2.1 the fiber is split into number of segments and the effects of dispersion and nonlinearity is evaluated individually in each of the segments and added. The effect of dispersion is evaluated at the middle of the segment only and the effect of nonlinearity is evaluated at the boundary of the segment. [6].

Now depending upon the initial width T_0 and peak power P_0 of the incident pulse, either dispersive or nonlinear effects dominate along the fiber. That means depending upon the relative magnitudes of $L_{D,}$ $L_{NL\ .}$ and L the pulses can evolve quite differently. Where L_D and L_{NL} are called dispersion length and nonlinear length respectively, which provide the length scales over which the over which dispersive and nonlinear effects become important for nonlinear propagation. These are related to pulse parameters according to the relations

$$L_D = \frac{T_0^2}{|\beta_2|} \quad , \quad L_{NL} = \frac{1}{\gamma P_0} \qquad \text{...........(2)}$$

Now if,

$L \ll L_{NL}$ and $L \ll L_D$, neither dispersive nor nonlinear effects play a significant role in pulse propagation.

$L \ll L_{NL}$ and $L \sim L_D$, then pulse evolution is then governed by GVD, and nonlinear effects play a minor role.

$L \ll L_D$ and $L \sim L_{NL}$, pulse evolution in the fiber is governed by SPM that produces changes in the pulse spectrum.

$L \sim L_{NL}$ and $L \sim L_D$, dispersion and nonlinearity acts together as the pulse propagates along the length of the fiber. The interplay of GVD and SPM effect lead to a qualitatively different behavior compared with that expected from GVD or SPM alone. [6].

CHAPTER III

Gaussian Pulse Propagation

In this chapter, Propagation of Gaussian pulse under the influence of dispersion and nonlinearity of the fiber is analysed. Combined effect of dispersion and nonlinearity in the unchirped Gaussian pulse is shown.

3.1 Effects of Dispersion

Gaussian pulse is chosen to study the impairments caused by the fiber. For Gaussian pulse profile offers closed form analytic solution to effects of dispersion and non linearity, it is easier to predict the effect of each parameter of the pulse such as fwhm, chirp etc. further spectrum of the Gaussian pulse is also takes the Gaussian shape.

Incident field of the Gaussian pulse is defined as follows

$$U(0,T) = \exp\left(-\frac{T^2}{2T_o^2}\right) \qquad - (2.1)$$

where To be the full width at half maximum ($\frac{1}{e}$ of the maximum).

For given β_2 the dispersion length of the fiber is given by $L_D = \frac{T_o^2}{|\beta_2|}$. For a given fiber length, short pulses broaden more because of a smaller dispersion length.

In case of chirped Gaussian pulse the incident field is given as

$$U(0,T) = \exp\left(-\frac{(1+iC)T^2}{2T_o^2}\right) \qquad - (2.2)$$

Where C is the chirp parameter.

Because of GVD, different frequency components of a pulse travel at slightly different speeds along the fiber. More specifically red components travel faster than blue components in the normal-dispersion regime ($\beta_2 > 0$), while the opposite occurs in the anomalous-dispersion regime ($\beta_2 < 0$). The pulse can maintain its width only if all spectral components arrive together. Any time delay in the arrival of different spectral components leads to pulse broadening. [6].

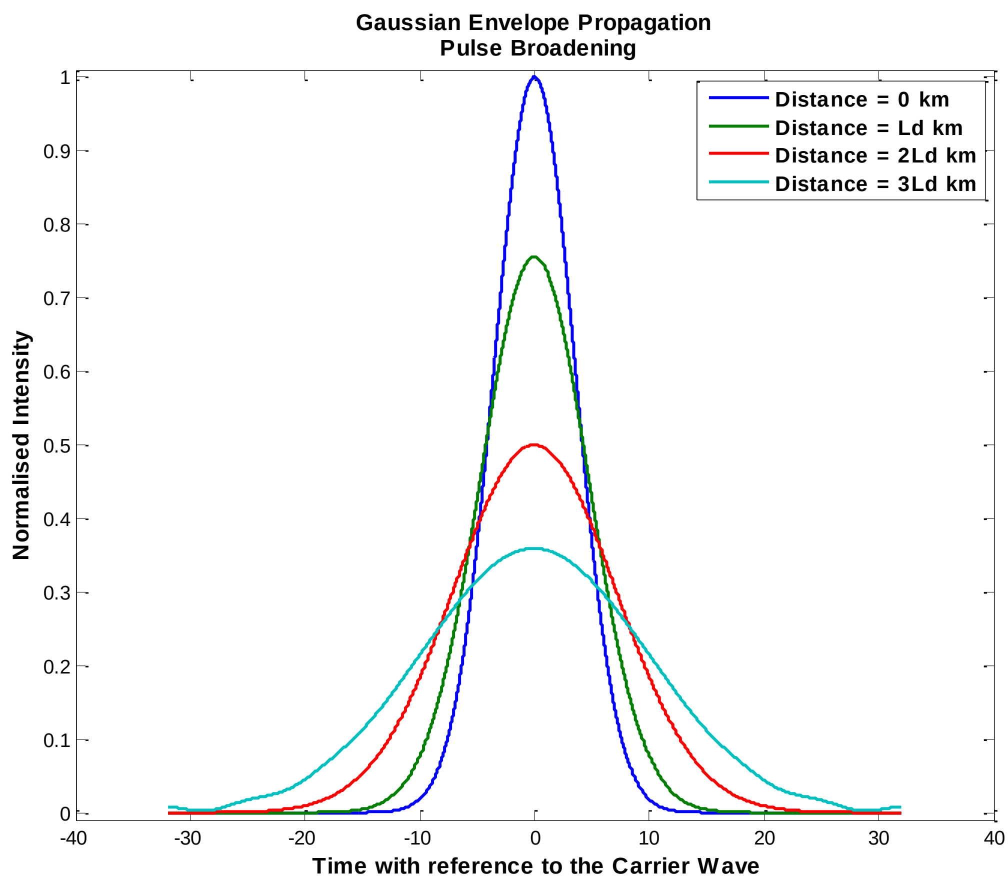

Figure 3.1 Gaussian Envelope Pulse Propagation – Effect of Dispersion.

Figure 3.1 shows the broadening of unchirped Gaussian pulse for different dispersion length LD. The extent of broadening is governed by the dispersion length LD. At z = LD, the Gaussian pulse broadens by factor of $\sqrt{2}$.

The instantaneous frequency increases linearly from the leading to the trailing edge

(up-chirp) for C > 0, while the opposite occurs (down-chirp) for C < 0.
An unchirped pulse (C = 0) broadens monotonically and develops a negative chirp. But chirped pulses may broaden or compress depending on whether β_2 and C have the same or opposite signs.

When $\beta_2 C > 0$, a chirped Gaussian pulse broadens monotonically at a rate faster than that of the unchirped pulse since the dispersion-induced chirp adds to the input chirp because the two contributions have the same sign.

For $\beta_2 C < 0$. pulse gets compressed till GVD and chirp acts in the opposite direction and cancelling the effect of each other. Pulse attains the minimum width beyond which effect of GVD begins to dominate

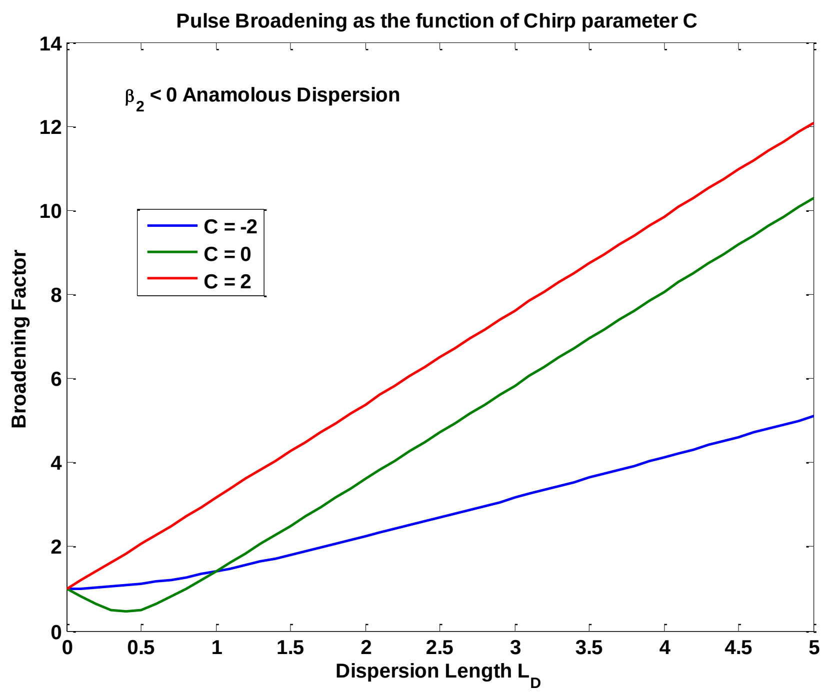

Figure 3.2 Pulse Broadening Factor vs. Dispersion Length

3.2 Effects of Nonlinearity

Most of the nonlinear effects in optical fibers therefore originate from nonlinear refraction, a phenomenon referring to the intensity dependence of the refractive index. The intensity dependence of the refractive index leads to a large number of interesting nonlinear effects; the two most widely studied are known as self-phase modulation (SPM) and cross-phase modulation (XPM).

Self-phase modulation refers to the self-induced phase shift experienced by an optical field during its propagation in optical fibers. Among other things, SPM is responsible for spectral broadening of ultra short pulses and formation of optical solitons in the anomalous-dispersion regime of fibers. Cross-phase modulation (XPM) refers to the nonlinear phase shift of an optical field induced by another field having a different wavelength, direction, or state of polarization. XPM is responsible for asymmetric spectral broadening of co-propagating optical pulses.

Another type of non-linearity due to third order susceptibility are Stimulated Brillioun Scattering (SBS) and Stimulated Raman Scattering (SRS). Above two inelastic scattering are characterized by threshold power beyond which their effects are significant. [6]. Nonlinear properties of the optical fiber is quantified through the non-linear coefficient γ whose typical value for standard SMF fiber is 2 $W^{-1}km^{-1}$. Dispersion and nonlinearity act together as the pulse propagates along the fiber. The interplay of the GVD and SPM effects can lead to a qualitatively different behaviour compared with that expected from GVD or SPM alone

.

Figure 3.3 illustrates the spectral broadening of the optical pulse due to non-linearity acting alone in the fiber. Additional frequency components generated through various nonlinear process leads to broadening of the pulse spectrum.

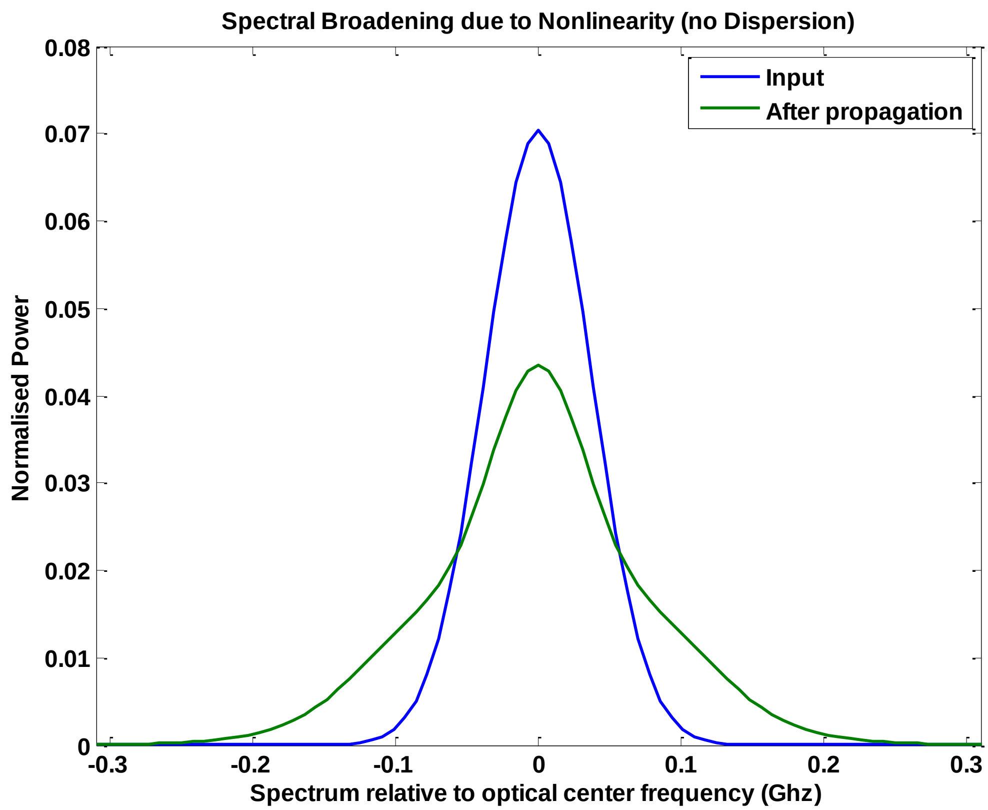

Figure 3.3 Effect of Nonlinearity on Spectral Broadening

Figure 3.4 illustrates the combined effect of nonlinearity and dispersion in the fiber acting together in two different dispersion regimes. In Normal Dispersion regime where $\beta_2 > 0$, presence of nonlinearity leads to shortening of the pulse spectrum, leading to larger pulse spread in the time domain

In Anomalous Dispersion regime where $\beta_2 < 0$, presence of nonlinearity leads to spectral broadening. leading to shorter pulse spread in the time domain. Hence if we could manage the nonlinearity such that it compensates the pulse broadening due to dispersion we could maintain the pulse shape throughout the fiber.

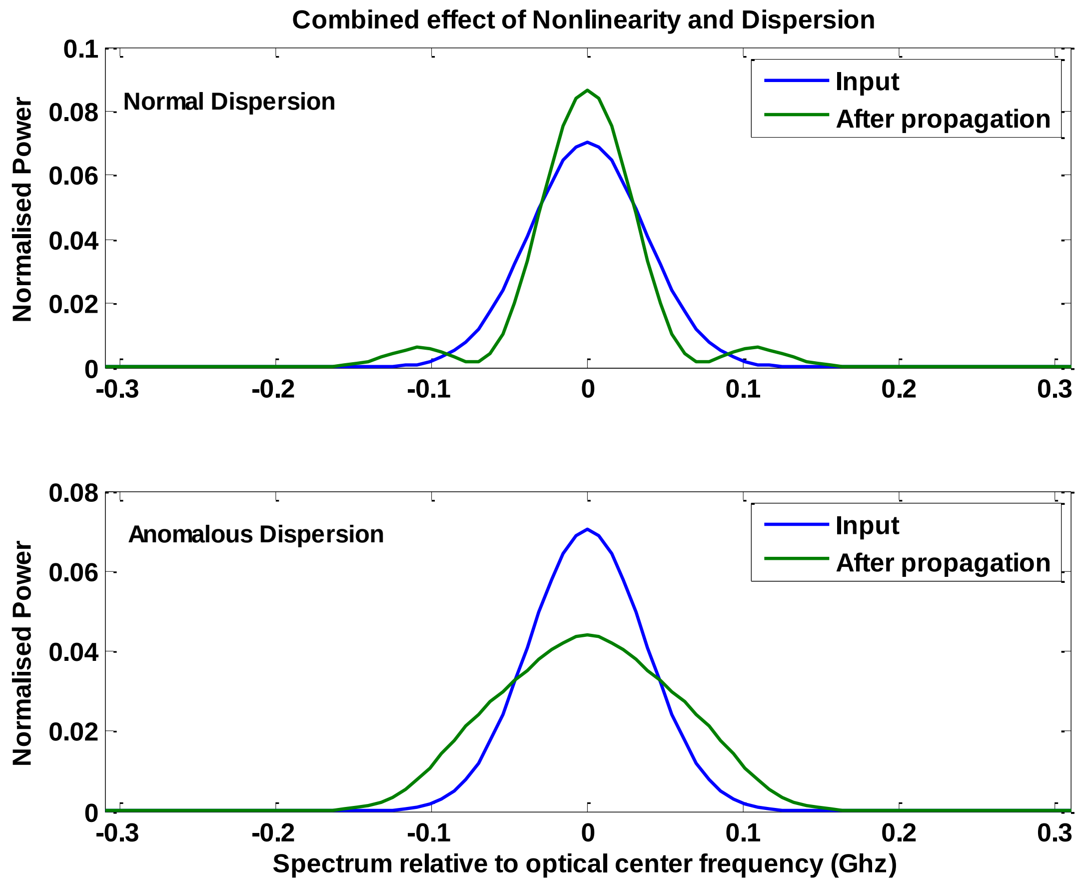

Figure 3.4 Combined Effect of Nonlinearity and Dispersion.

In this chapter we discussed the evolution of Gaussian pulse propagating through the fiber under the influence of dispersion and nonlinearity. In the next chapter we will discuss the evolution of stream of pulse generated by the PRBS source through the fiber.

CHAPTER IV

Data Modulation Formats

In the last chapter, evolution of Gaussian pulse is discussed. In this chapter, we discuss of evolution of stream of pulses propagating inside the fiber. Generation and Modulation of PRBS bit stream for OOK and DPSK modulation formats is discussed. OOK data format in both RZ and NRZ line coding version is studied. Transmitter and Receiver blocks of NRZ OOK and NRZ DPSK is detailed.

4.1 NRZ-OOK Format

For a long time, non-return-to-zero on-off-keying (NRZ-OOK) has been the dominant modulation format in IM/DD fiber-optical communication systems. NRZ format is most popular because of following reasons. First, it requires a relatively low electrical bandwidth for the transmitters and receivers (compared to RZ); second, it is not sensitive to laser phase noise (compared to PSK); and last, it has the simplest configuration of transceivers.

However, it needs larger bandwidth, hence it is not the best choice for high capacity optical systems. However, due to its simplicity, and its historic dominance, NRZ would be a good reference for the purpose of comparison.

The block diagram of a NRZ transmitter is shown in Figure 4.1 where electrical signal is modulated with an external intensity modulator. The intensity modulator converts an OOK electrical signal with data rate of R_b into an OOK optical signal at the same data rate. The optical pulse width of each isolated digital “1” is equal to the inverse of the data-rate. To detect a NRZ optical signal, a simple photodiode is used at the receiver, which converts optical power of signal into electrical current. This is called direct detection (DD).

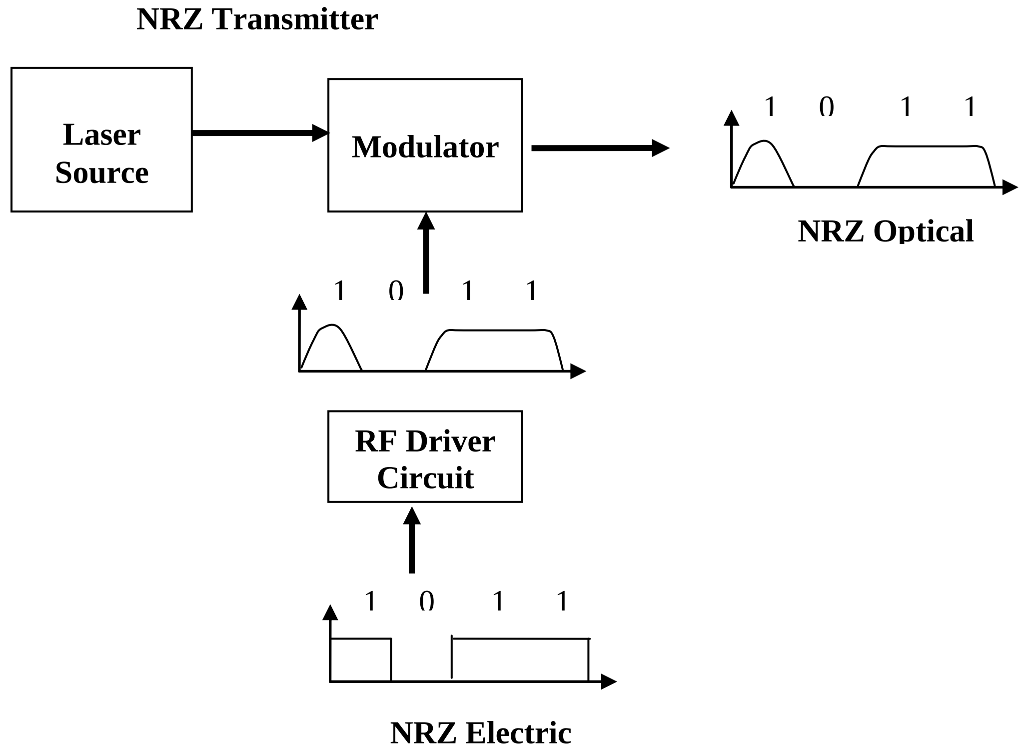

Figure 4.1 NRZ OOK Transmitter Block Diagram

Figure 4.2 shows the spectrum of NRZ OOK sequence with datarate of 10Gbps. NRZ optical signal has been found to be less resistive to GVD-SPM effect in transmission compared to its RZ counterparts. This is due to the fact that different data patterns in a PRBS NRZ data stream require different optimum residual dispersion for the best eye opening. For example, an isolated digital "1" would generate more self-phase modulation (SPM) effect than continuous digital "1"s. i.e. larger intensity change over the bit interval. Since SPM can be treated as an equivalent signal frequency chirp, it modifies the optimum value of the dispersion compensation in the system. The difference in the optimum dispersion compensation between an isolated digital "1" and continuous digital "1"s makes it impossible to optimize the residual dispersion in the system and thus makes the system performance vulnerable to the data pattern-dependent fiber nonlinear effect. This effect is especially important in long distance fiber-optic systems.

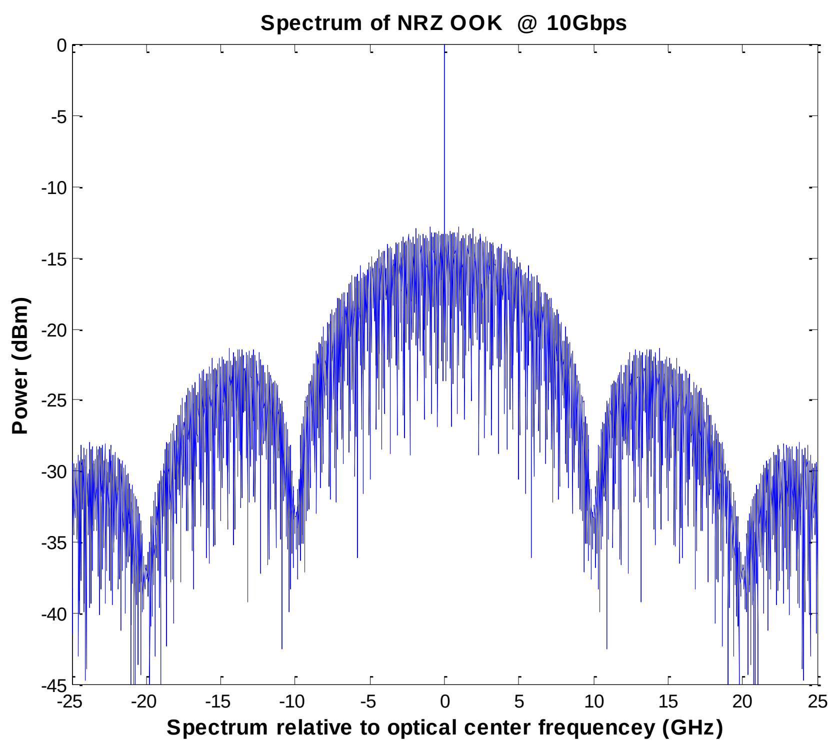

Figure 4.2 Spectrum of 10 Gbps NRZ-OOK Sequence

Link Setup

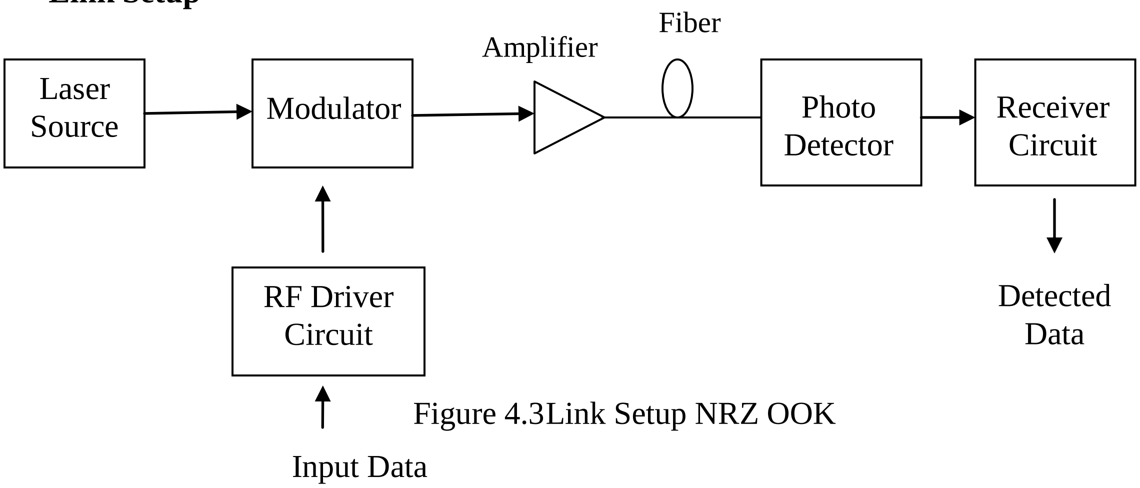

Figure 4.3Link Setup NRZ OOK

4.2 RZ-OOK Format

In RZ 'return-to-zero' format width of optical signal is smaller than its bit period. Usually a clock signal with the same datarate as electrical signal is used to generate RZ shape of optical signals. First, NRZ optical signal is generated using an external intensity modulator. Then, it is modulated by a synchronized pulse train (clock) with the same datarate as the electrical signal using another intensity modulator.

The spectrum of RZ is also shown in Figure 4.4 Compared to NRZ; it has a wider spectrum because of its narrower pulse width. This would lead to less spectrum efficiency for RZ in a WDM system.

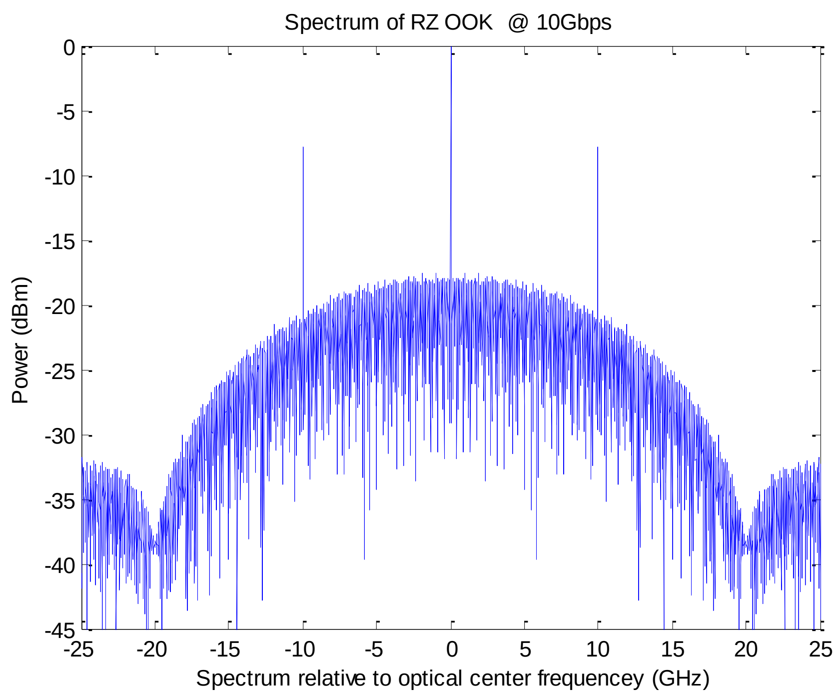

Figure 4.4 Spectrum of 10 Gbps RZ sequences

4.3 NRZ- DPSK Format

Differential-phase-shift-keying (DPSK) is the most often used format in the phase modulation schemes. The block diagram of a typical NRZ-DSPK transmitter is shown below.

Before getting into the external phase modulator, NRZ electrical signal has to be pre-encoded by a DPSK encoder. In a DPSK encoder, the NRZ data is converted by a NOR gate first and then combined with its one-bit delay version by a XOR gate. This DPSK encoded electrical signal is then used to drive an electro-optic phase modulator to generate a DPSK optical signal. A digital “1” is represented by a π phase change between the consecutive data bits in the optical carrier, while there is no phase change between the consecutive data bits in the optical carrier for a digital “0”. A very important characteristic of NRZ-DPSK is that its signal optical power is always constant.

A one-bit-delay Mach-Zehnder Interferometer (MZI) is usually used as a DPSK optical receiver. MZI is used to correlate each bit with its neighbor and make the phase-to-intensity conversion.

Intuitively, because of its constant optical power the performance of NRZ-DPSK should not be affected by optical power modulation-related nonlinear effects such as SPM and XPM contribute to waveform distortion to some extent [4]. In a long distance DPSK system with optical amplifiers, nonlinear phase noise is usually the limiting factor for phase-shift-keying optical signals.

Transmitter Block Diagram:

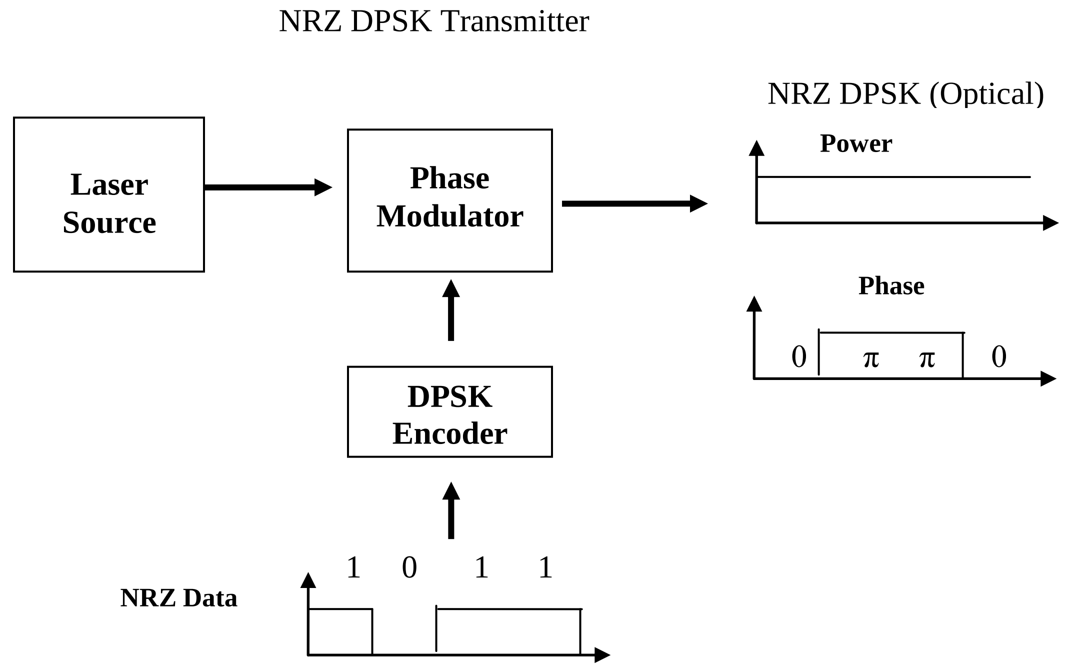

Figure 4.5 Block Diagram of NRZ-DPSK Transmitter

Receiver Block Diagram:

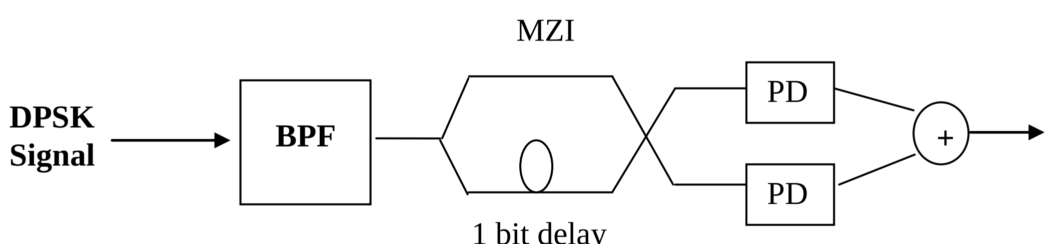

Figure 4.6 Block Diagram of NRZ-DPSK Receiver

Figure 4.7 shows the Input sequence generated by the PRBS generator and the corresponding DPSK encoded data. 0 shows the distorted DPSK signal after propagating through the fiber.

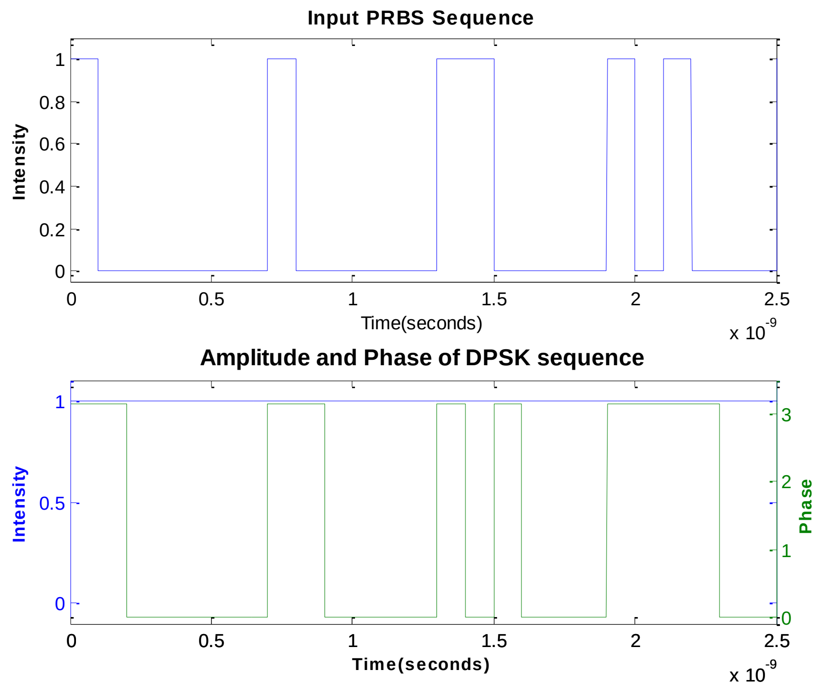

Figure 4.7 DPSK Encoded sequence

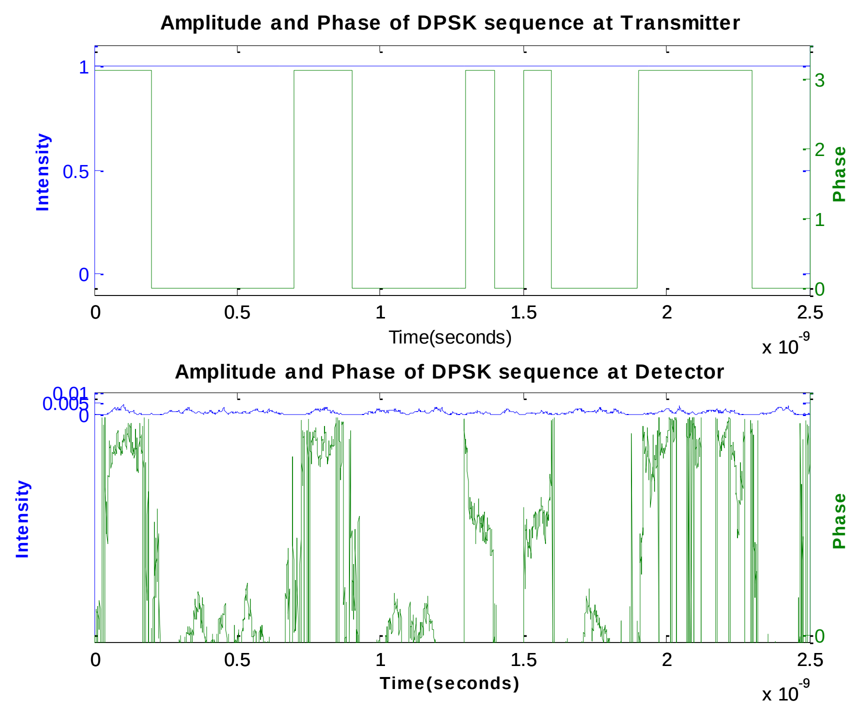

Figure 4.8 DPSK Envelope & Phase at Transmitter and Detector

CHAPTER V

Link Simulation and Estimation of BER

In this chapter, we discuss about the various parameters considered for the simulation. Method for BER estimation is also discussed.

5.1 Simulation Parameters

- Pulse envelope of the modulating signal(either at 10 Gbps or at 40 Gbps data rate) is used as the input waveform for simulation
- Train of 2000 PRBS pulses is generated using the PRBS generator with randomness of 2^9-1 corresponding pattern length is 511 bits.
- Simulation Time window length is 50ns which is sampled at 8 THz.
- Duration between samples is 0.125 ps. Hence based on the bit rate either 200 samples (40Gbps) or 800 samples(10Gbps) are taken per bit period.
- **Filter to model the finite Rise time of the MZI Modulator**
    - To Model the finite rise time of the modulator driver circuit, input sequence is passed through the Bessel filter.
    - Bessel filter of order 5 is chosen to provide the rise time of 25% of the bit duration. Cutoff frequency of the filter is set accordingly.
- BER is estimated for pulse propagating through different lengths (km) of standard SMF fiber. In another case, Input power of the PRBS sequence is varied.
- Eye Pattern of the signal detected at the receiver is generated.
- Eye Opening Penalty and SNR of the received signal is calculated.
- Plot of log value of BER versus length and log BER versus Power is generated.

5.2 BER Estimation

Bit error rate (BER) is the ratio between the number of bits received in error to the total number of bits received. In essence, BER is the probability of receiving a single bit in error.

In the study of the performance degradation of the communication link, signal, impairments due to the noise in the receiver during detection must be constant for all measurement. Keeping this in mind, simulation is carried out such that noise added to the detected signal is constant in all the cases of the ber measurement. From the datasheet of PIN receiver, Noise equivalent power of the detector is noted which is usually measured as W/√Hz. We can calculate the noise power at the receiver as follows.

Noise Power = Noise Equivalent Power (NEP) x √Bandwidth

Random Noise signal is generated with this calculated noise power as variance and with zero mean. For each case SNR of the signal is calculated which is equivalent to estimating the Q value .From the SNR value the ber of the system is estimated as follows.

$$\text{BER} = \frac{1}{2}\,\text{erfc}\left(\frac{\text{SNR}}{\sqrt{2}}\right) \quad \text{---- (5.1)}$$

Eye Opening Penalty:

Eye opening is defined as the difference (height) between minimum value of one (1) and the maximum value of zero (0). The eye opening penalty (EOP) is defined as the ratio of the height of the non distorted eye EOref to the height of the distorted eye EO,

$$\text{EOP} = 10\log\frac{EO_{ref}}{EO} \quad \text{--- (5.2)}$$

5.3 Results & Discussion

5.3.1 NRZ OOK Format

We plot the BER for different propagation distance at fixed input power as well as BER for different input power levels at the fixed propagation distance. In both the cases BER is estimated from the measured SNR levels at the receiver. Above two measurements are done for both 10 Gbps and 40 Gbps data rate. While estimating BER for different power levels propagation distance is fixed at 80km.

For 10 Gbps Date Rate

Case (i) :

Fixed Input Power = -10 dBm.

Dispersion Parameter D = 17 ps/km-nm

Propagation Distance L varied from 10 km to 90 km in steps of 10 km.

Case (ii) :

Fixed Distance = 80 km.

Dispersion Parameter D = 17 ps/km-nm

Input Power P is varied from -13 dBm to 0 dBm

(i) Eye Diagram at the Receiver at different propagation distance.

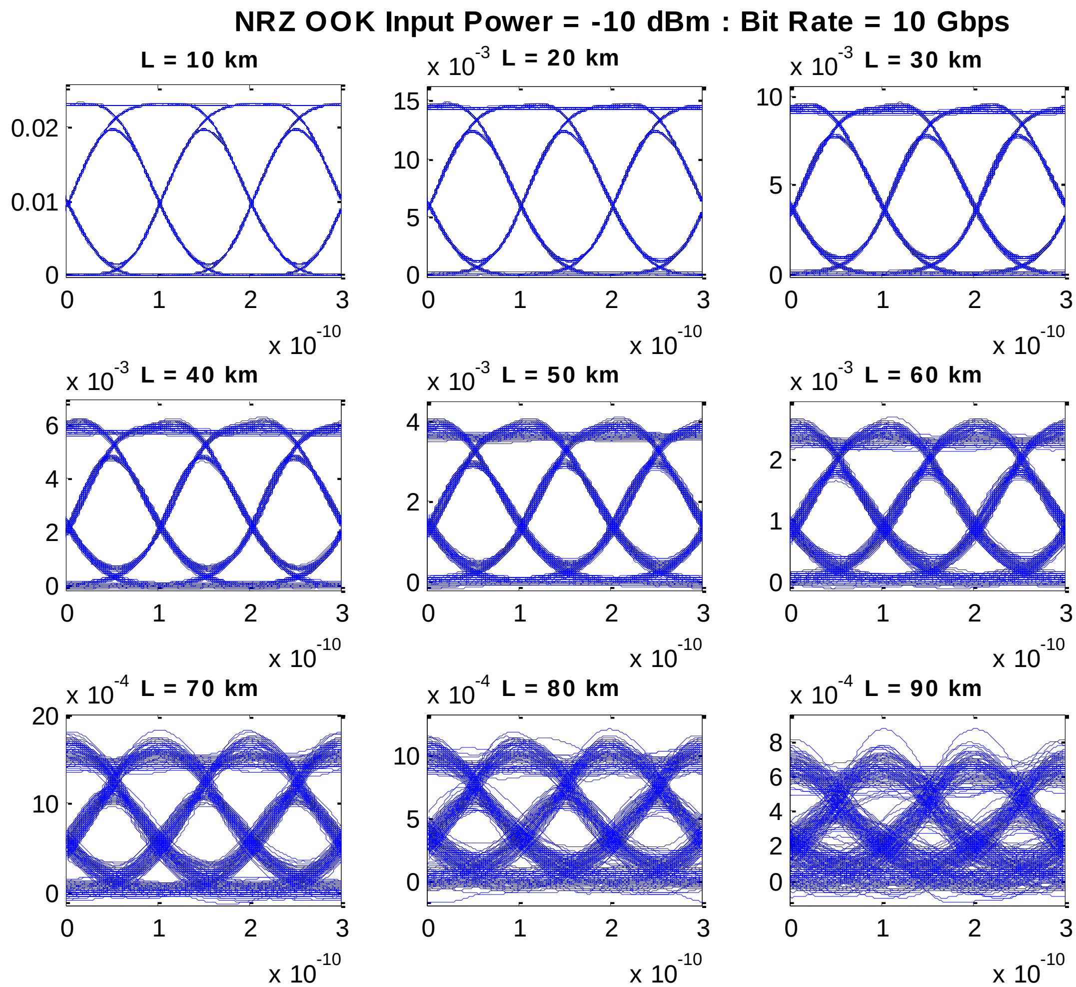

Figure 5.1 Eye Diagram at the Receiver – for Different Length (NRZ 10 Gbps)

With increase in the propagation distance, eye is progressively gets closed, this phenomenon is seen in Figure 5.1. Plot of the logarithm of BER versus distances is shown Figure 5.2 Figure 5.3 shows the trend of increase in the eye closure penalty for larger distance.

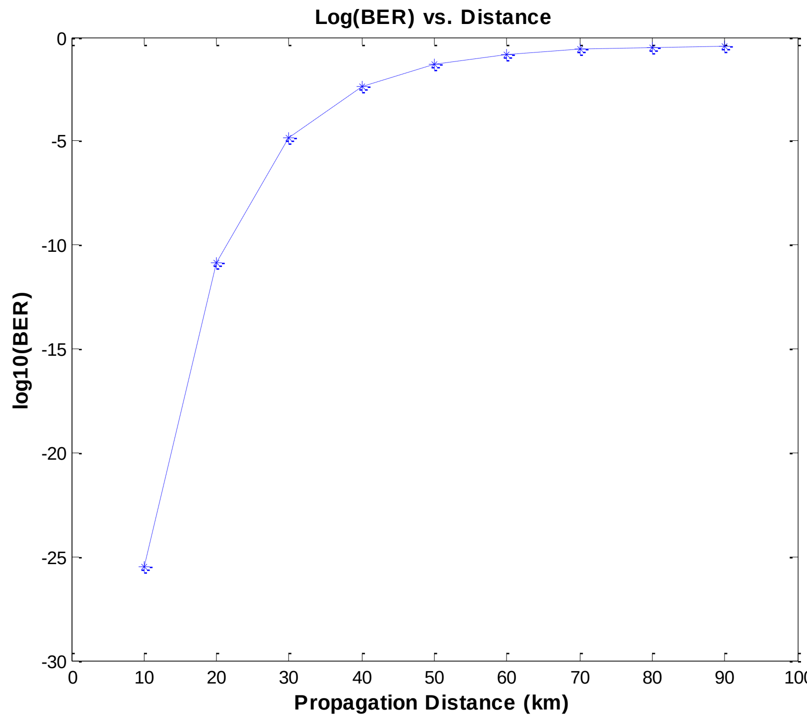

Figure 5.2 Log BER vs. Distance @ 10 Gbps NRZ OOK

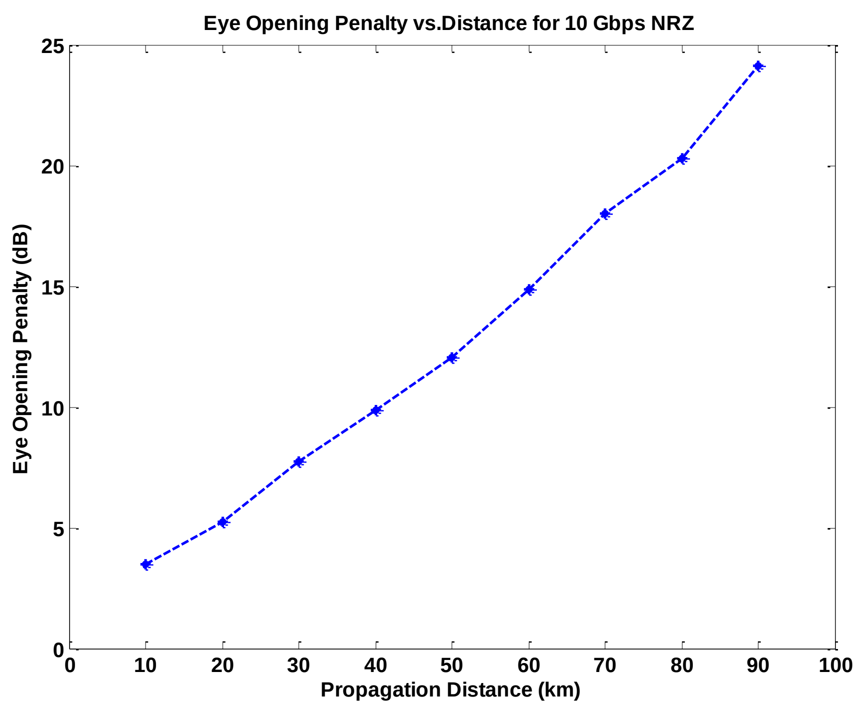

Figure 5.3 Eye Opening Penalty vs. Distance @ 10 Gbps NRZ OOK

(ii) Eye Diagram at the Receiver with different Input Power.

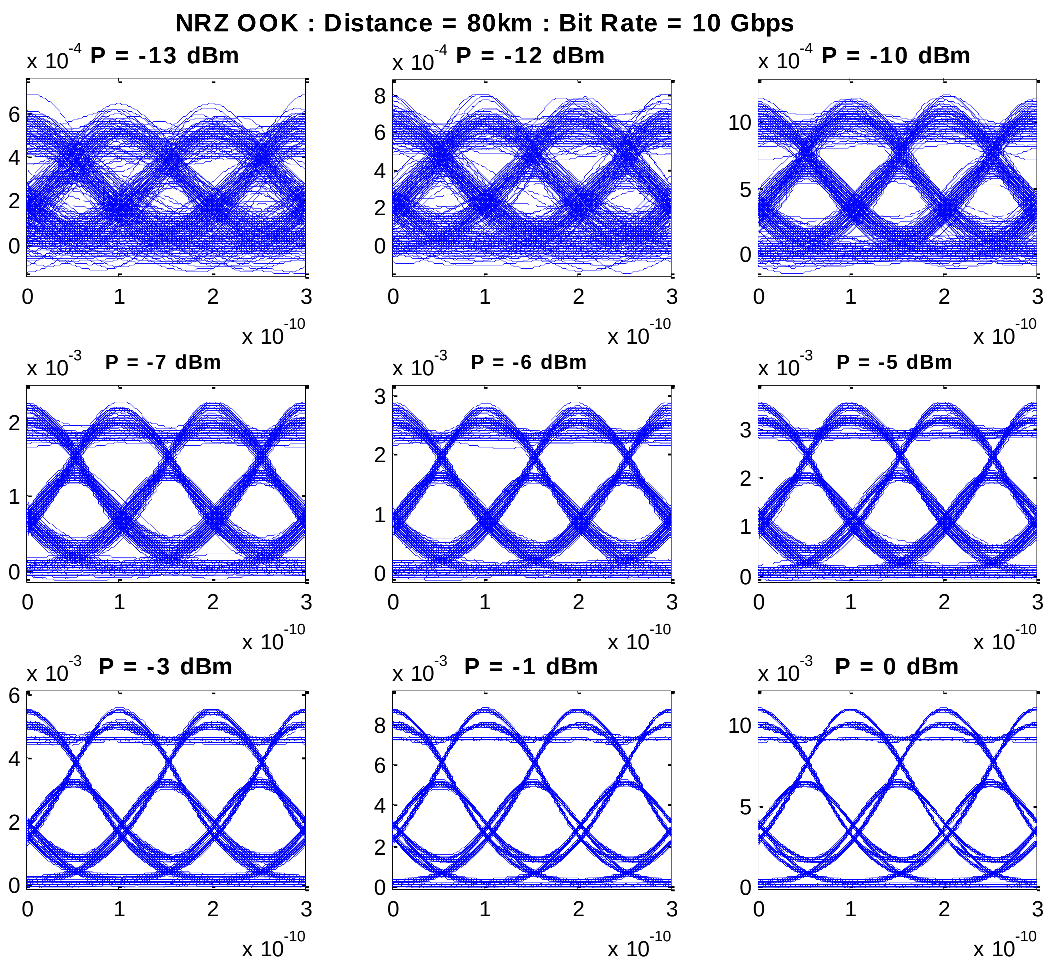

Figure 5.4 Eye Diagram at the Receiver - for different Power (NRZ 10 Gbps)

With increase in the input power, eye opening increases. This phenomenon is seen in Figure 5.4 Plot of the logarithm of BER versus input power is shown Figure 5.5

BER vs. Input Power at 10Gbps

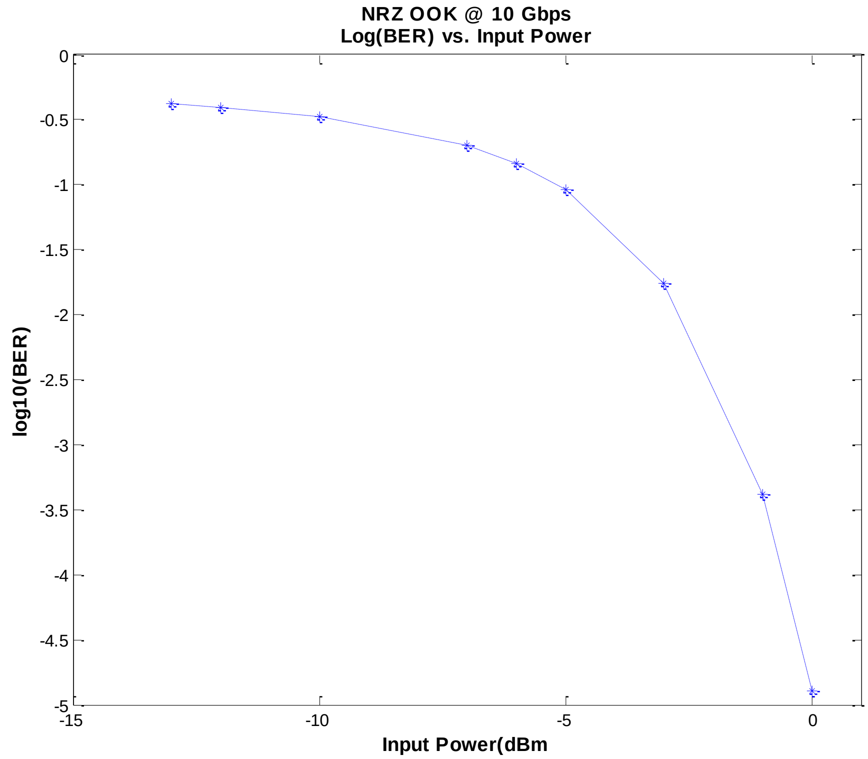

Figure 5.5 Log(BER) vs. Input Power

For 40 Gbps Date Rate

Case(i):

Fixed Input Power = -10 dBm.

Dispersion Parameter D = 17 ps/km-nm

Propagation Distance L varied from 2 km to 18 km in steps of 2 km.

Case(ii):

Fixed Distance = 20 km.

Dispersion Parameter D = 17 ps/km-nm

Input Power P is varied from -20 dBm to 0 dBm

At 40 Gbps data rate, effect of dispersion is more pronounced. Hence to have realistic numbers for comparison simulation is run for shorter distance. Logarithm of BER is plotted versus length of fiber and Input Power.

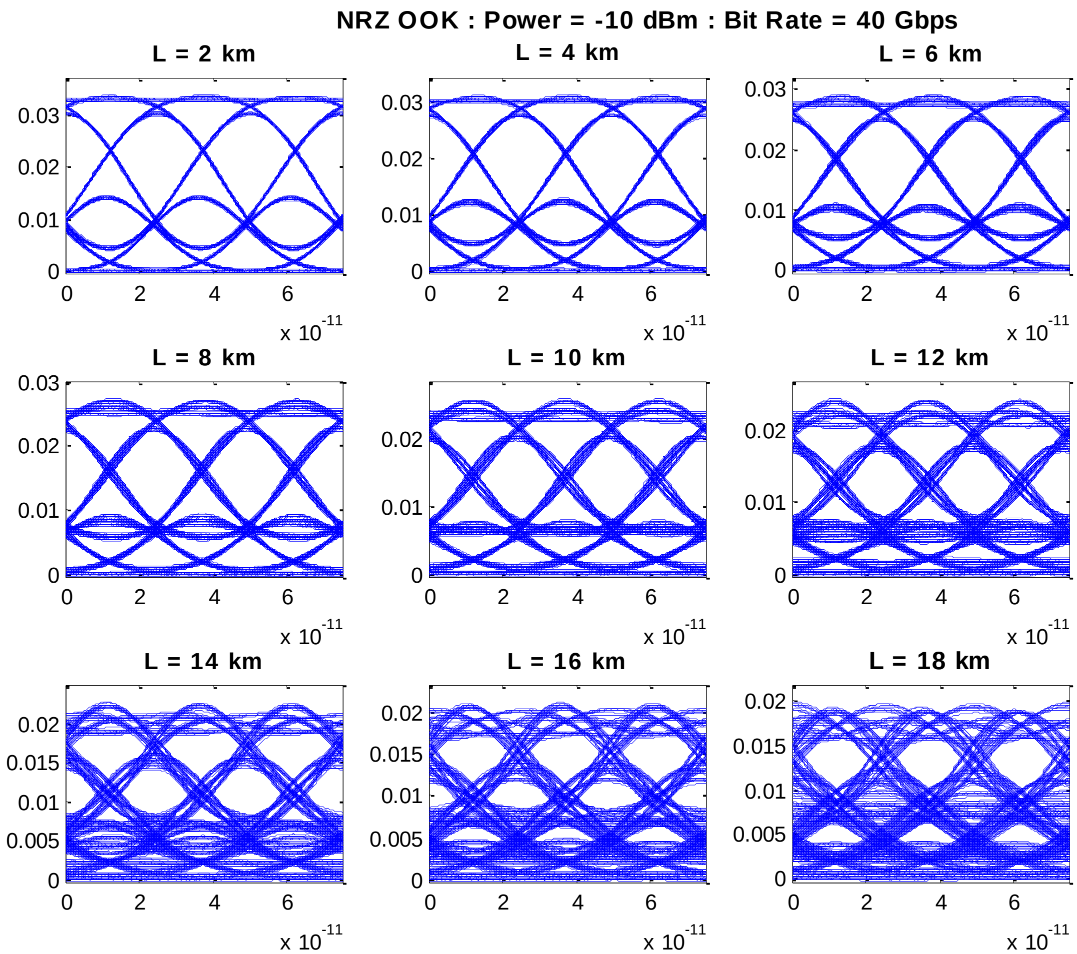

Figure 5.6 Eye Diagram at the Receiver – for different Length (NRZ 40 Gbps)

From Figure 5.6 it is evident that with increase in the propagation distance, eye gets closed. Plot of the logarithm of BER versus distances is shown Figure 5.7

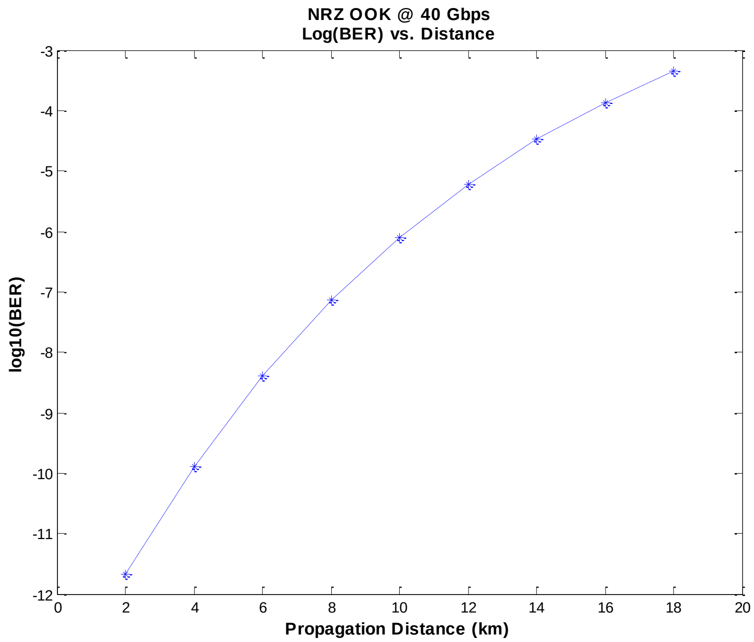

Figure 5.7 Log BER vs. Distance @ 40 Gbps NRZ OOK

Case (ii) : Eye Diagram for different Distance @ 40 Gbps

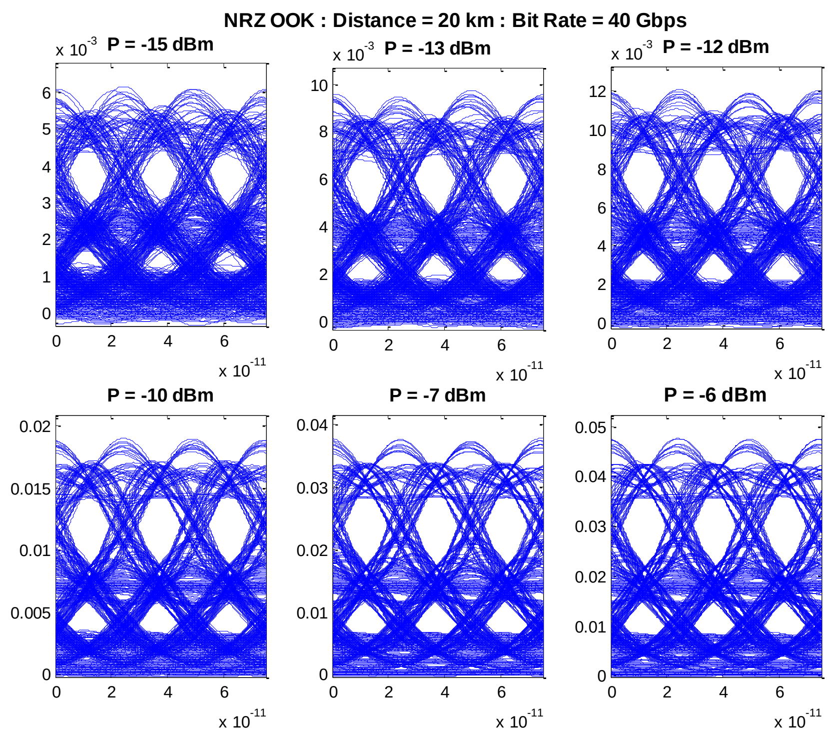

Figure 5.8 Eye Diagram at the Receiver - for different Power (NRZ 40 Gbps)

With increase in the input power, eye opening increases. This phenomenon is seen in Figure 5.8 Plot of the logarithm of BER versus input power is shown Figure 5. Figure 5.9 shows the trend of increase in the eye closure penalty for larger distance.

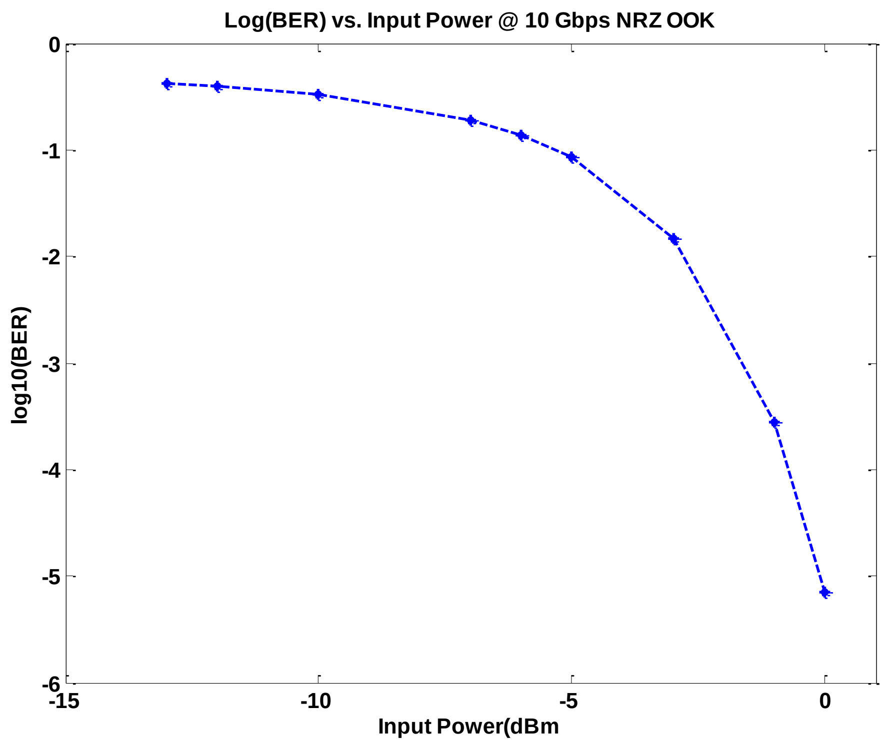

Figure 5.9 Log BER vs. Input Power @ 40 Gbps NRZ OOK

5.3.2 RZ-OOK Format

Similar to that of NRZ format. Here also we estimate BER for different propagation distance at fixed input power and BER for different input power levels at the fixed propagation distance. In both the cases BER is estimated from the SNR at the receiver.

For 10 Gbps Data Rate:

Case(i):

Fixed Input Power = -10 dBm.

Dispersion Parameter D = 17 ps/km-nm

Propagation Distance L varied from 10 km to 90 km in steps of 10km.

Eye Diagram for different Lengths @ 10 Gbps

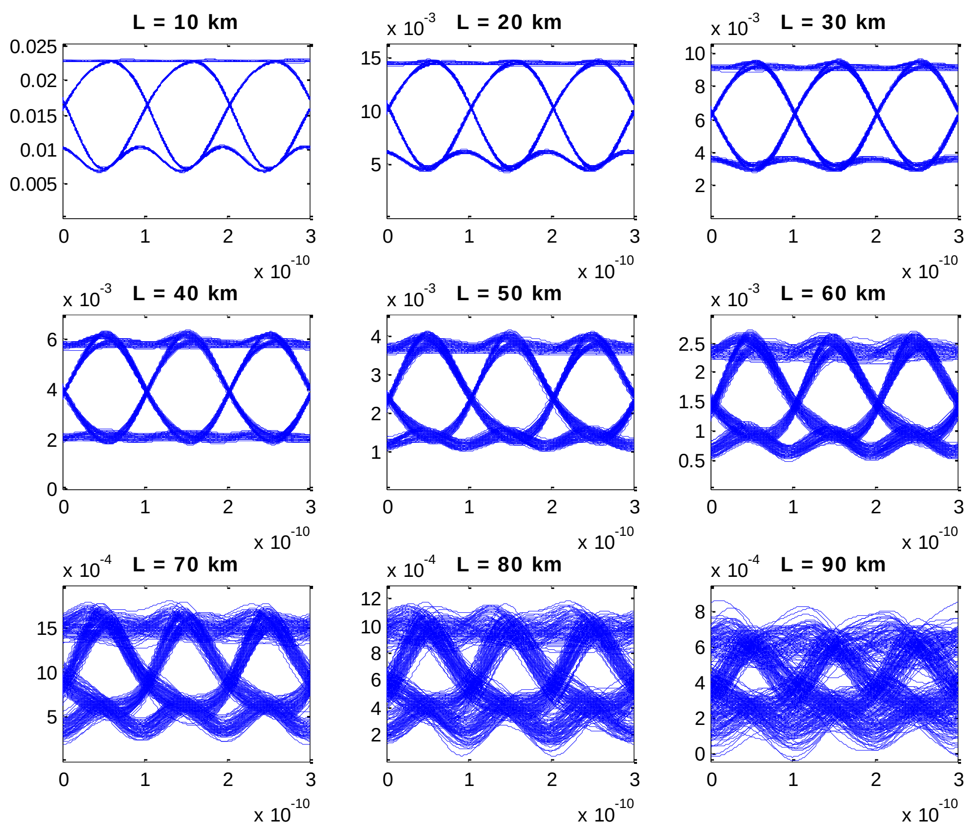

Figure 5.10 Eye Diagram for Different Distance @ 10 Gbps RZ OOK

With increase in the propagation distance, eye is progressively gets closed, this phenomenon is seen in Figure 5.10 Plot of the logarithm of BER versus distance is shown in the Figure 5.11. Figure 5.12 shows the trend of increase in the eye closure penalty for larger distance.

Plot of BER vs. Distance

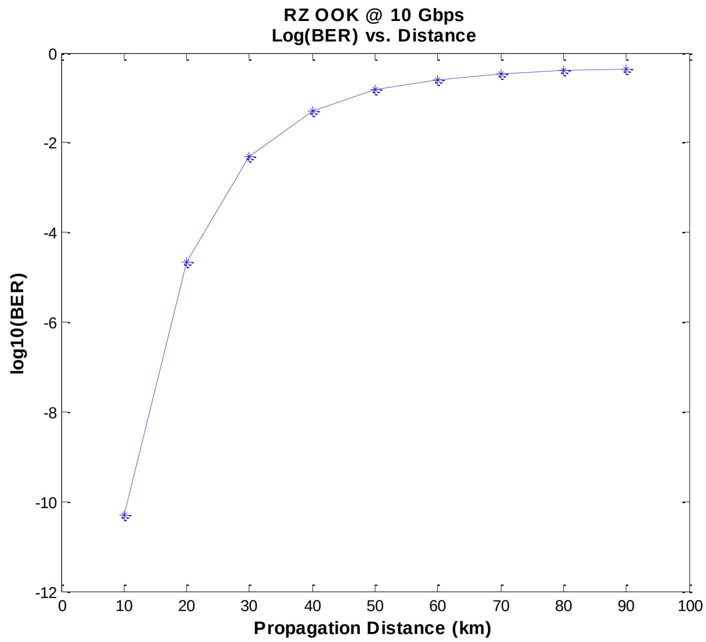

Figure 5.11 Log(BER) vs. Distance (RZ OOK 10 Gbps)

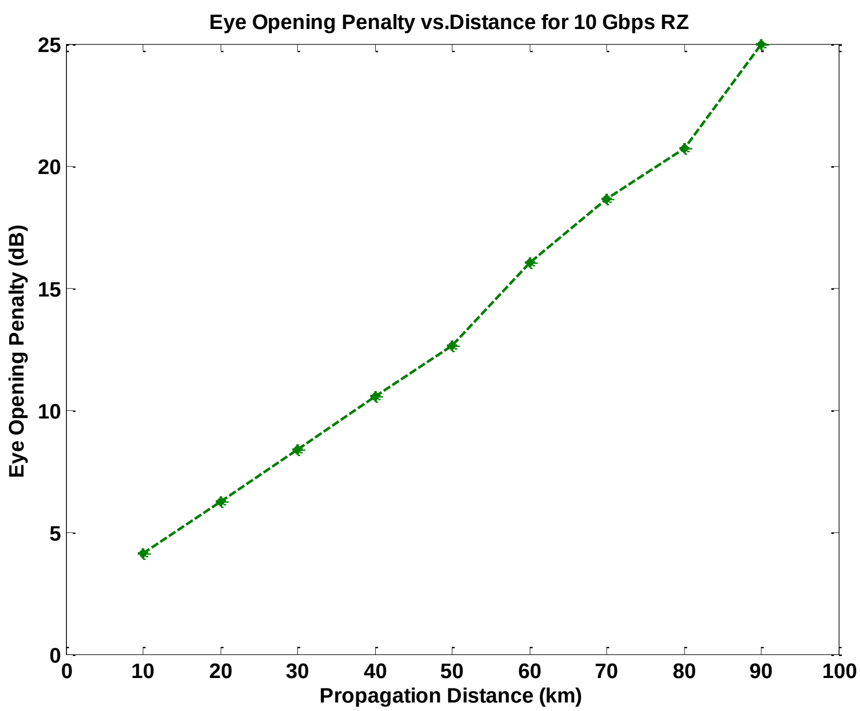

Figure 5.12 Eye Opening Penalty vs. Distance @10 Gbps RZ OOK

Case (ii):

Fixed Distance = 80 km.

Dispersion Parameter D = 17 ps/km-nm

Input Power P is varied from -13 dBm to 0 dBm

Eye Diagram for different Power @ 10 Gbps

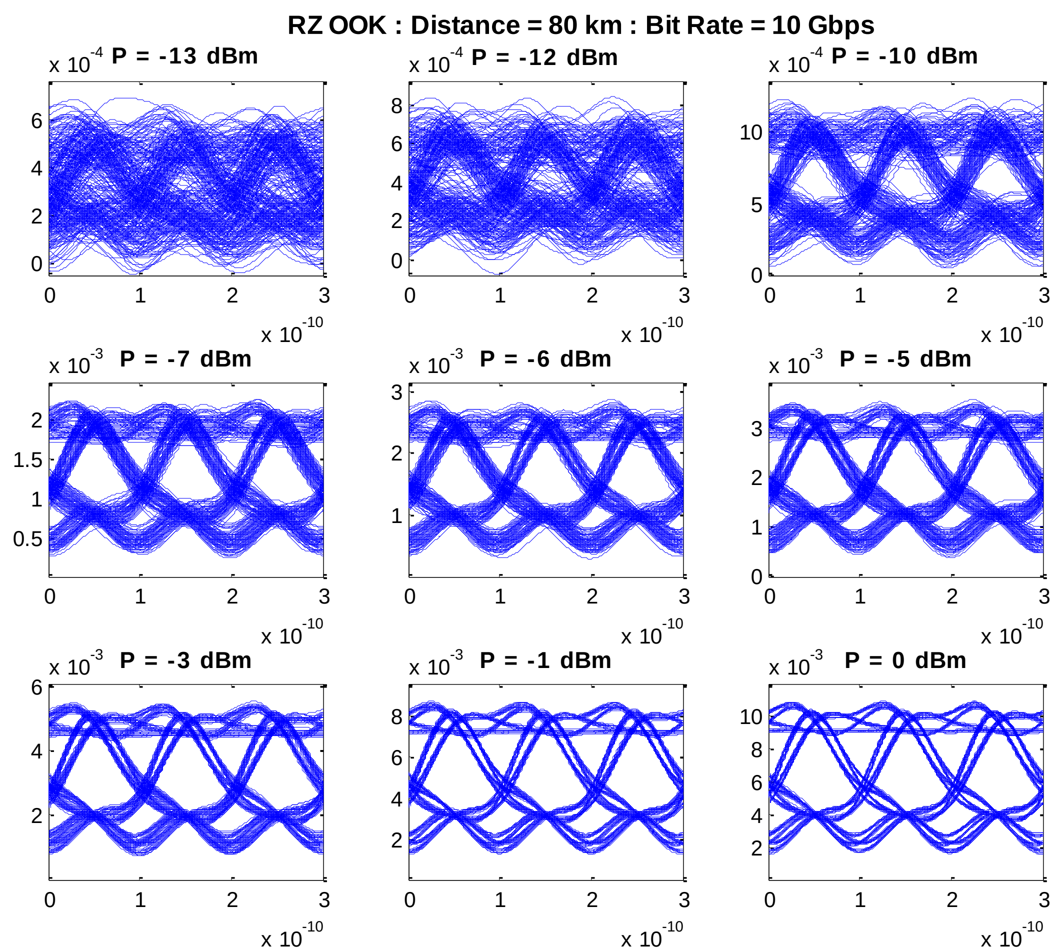

Figure 5.13 Eye Diagram for Different Power @ 10 Gbps RZ OOK

With increase in the input power, eye opening increases. This phenomenon is seen in Figure 5.13. Plot of the logarithm of BER versus input power is shown Figure 5.14

Plot of BER vs. Input Power

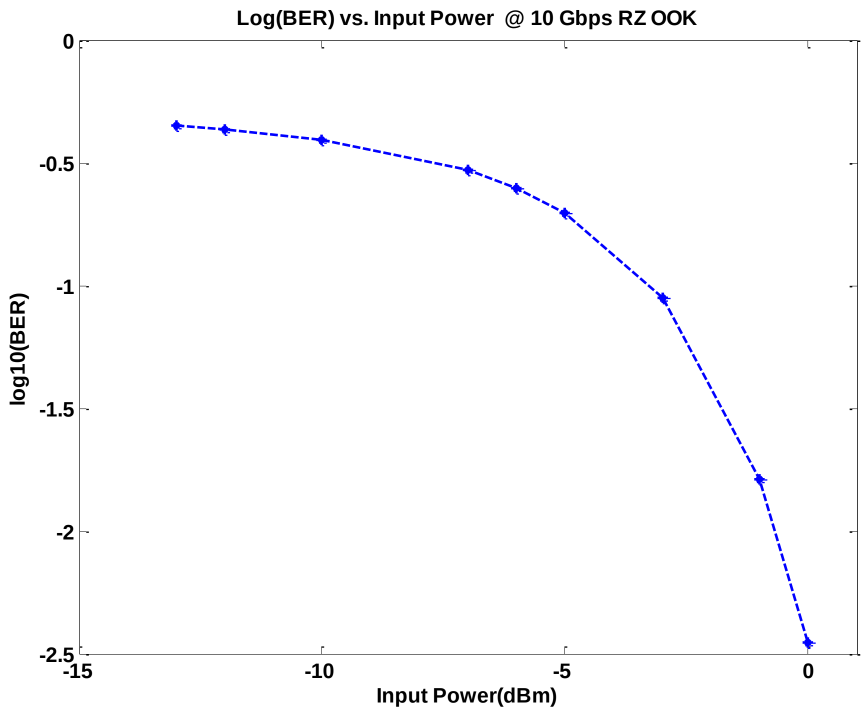

Figure 5.14 Log (BER) vs. Input Power @ 10 Gbps RZ

For 40 Gbps Data Rate:

Case (i):

Fixed Input Power = -10 dBm.

Dispersion Parameter D = 17 ps/km-nm

Propagation Distance L varied from 2 km to 18 km in steps of 2 km.

Eye Diagram for different lengths @ 40 Gbps

From Figure 5.15 it is evident that with increase in the propagation distance, eye gets closed. Plot of the logarithm of BER versus distances is shown Figure 5.16

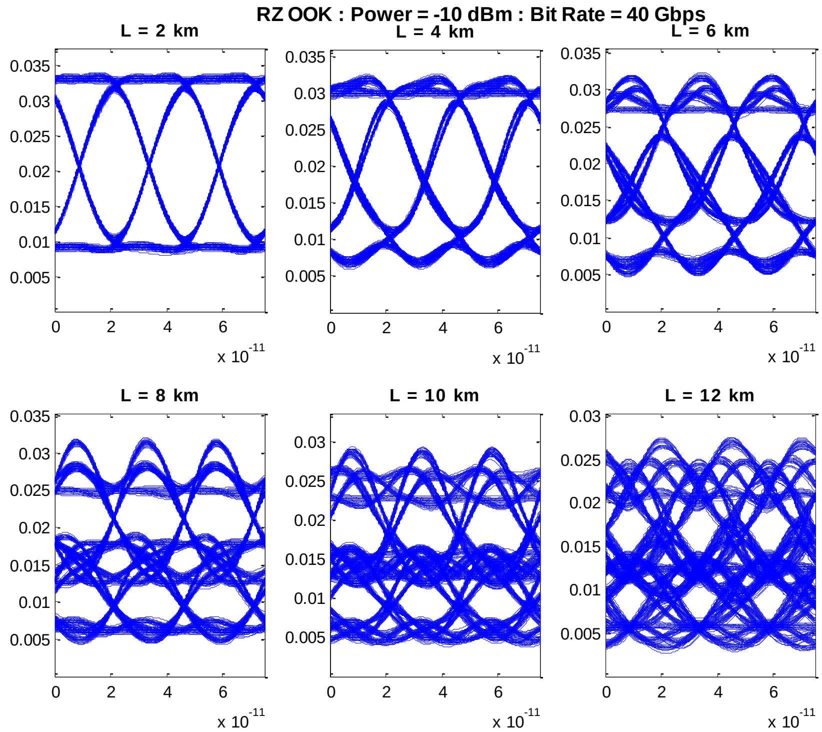

Figure 5.15 Eye Diagram for Different Distance @ 40 Gbps RZ OOK

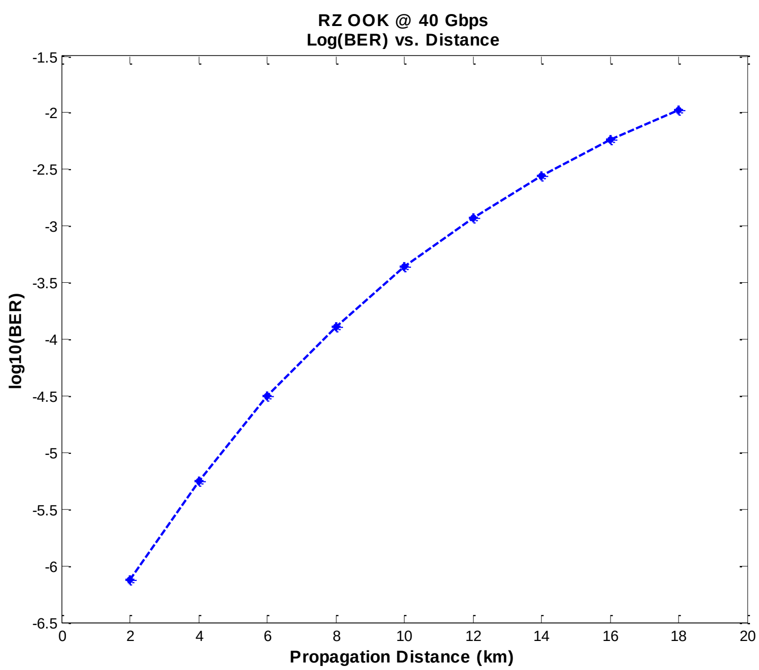

Figure 5.16 Log(BER) vs. Distance @40 Gbps RZ OOK

Case (ii):

Fixed Distance = 20 km.

Dispersion Parameter D = 17 ps/km-nm

Input Power P is varied from -20 dBm to 0 dBm

Eye Diagram for different Power @ 40 Gbps

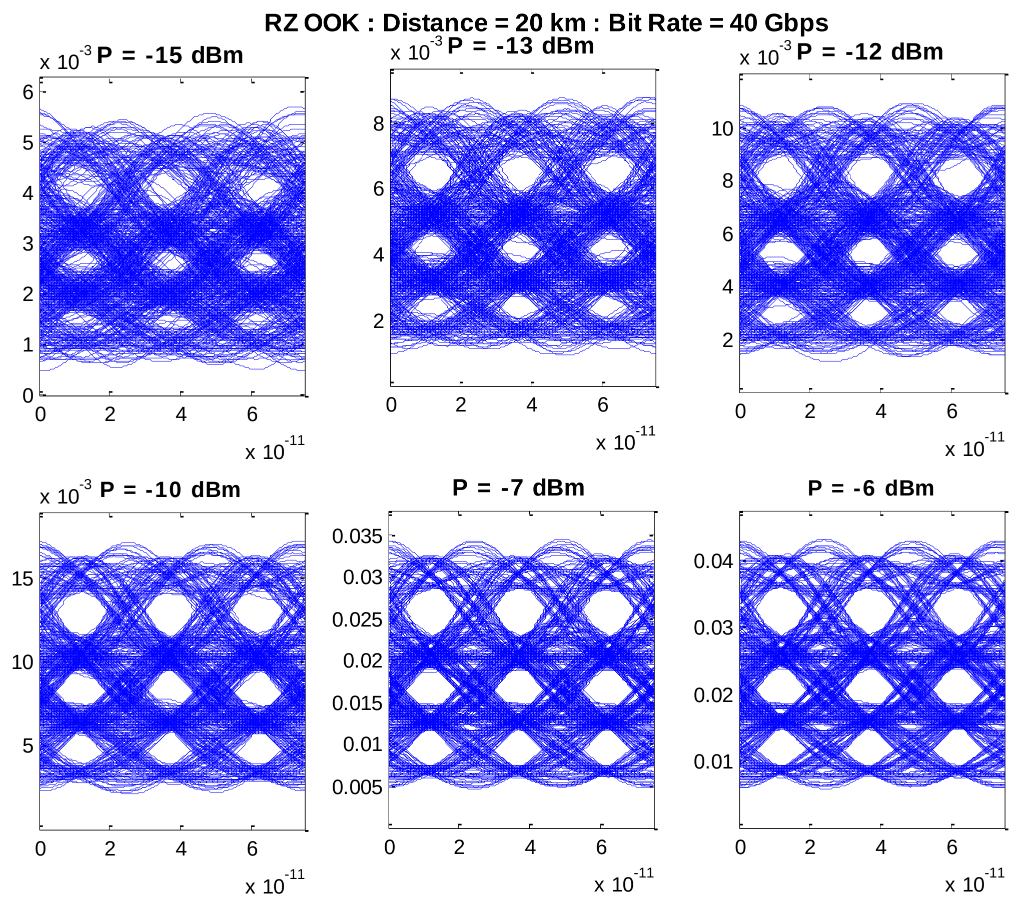

Figure 5.17 Eye Diagram at the Receiver – for Different Power (RZ 40 Gbps)

With increase in the input power, eye opening increases. This phenomenon is seen in Figure 5.17. Plot of the logarithm of BER versus input power is shown Figure 5.18

Plot of BER vs Input Power

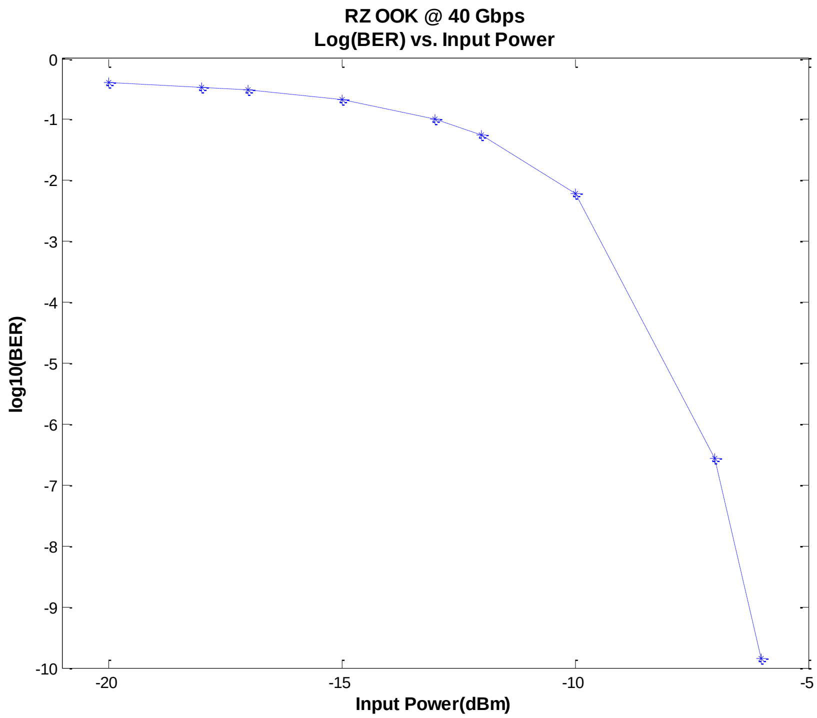

Figure 5.18 Log BER vs. Input Power @ 40 Gbps RZ OOK

5.3.3 Comparison of Performance of NRZ OOK and RZ OOK formats

In OOK NRZ and RZ line coding formats are compared for their BER performance both at 10 Gbps and 40 Gbps. Simulation parameters for each set is same. From the plot it is evident that NRZ OOK is better thant RZ OOK in an dispersion dominated communication links. This fact is due to the higher bandwidth occupied by the RZ pulse compared to that of NRZ pulse for the same bit rate.

Hence NRZ OOK has lower power penalty for dispersion compared to that of RZ OOK systems.

Eye Opening Penalty

Eye opening penalty is the one of the performance indicator for evaluation of optical systems in the presence of the noise. From Figure 5.19 it is evident that NRZ signals have lower penalty compared to that of RZ signal. This indicates higher ISI for signals modulated with RZ format which is due to the fact that RZ signal undergoes larger dispersion owing to higher bandwidth which is twice as that of NRZ signals.

;

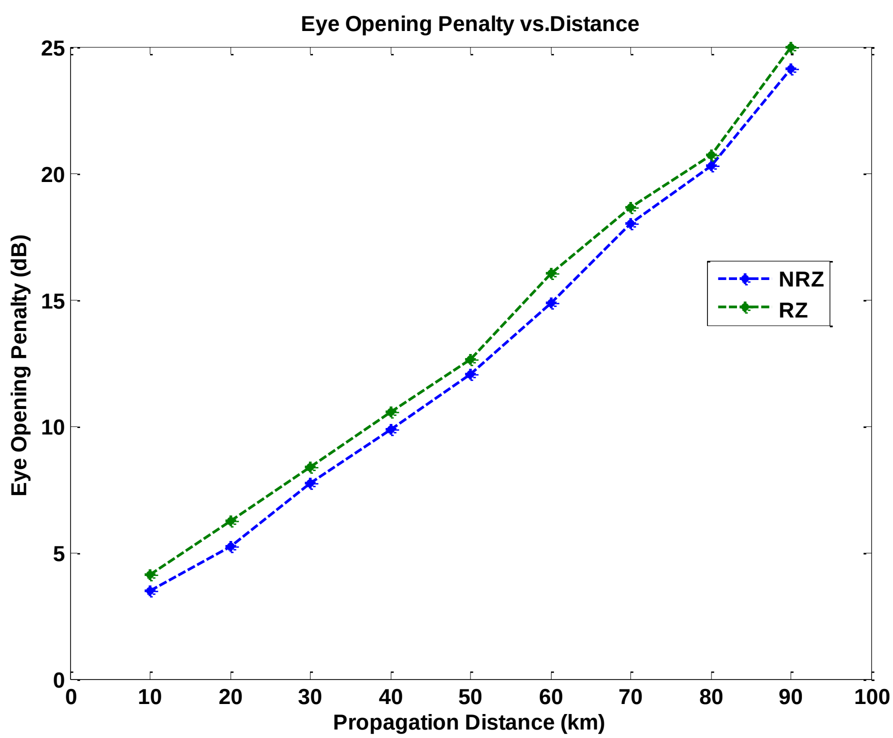

Figure 5.19 Eye Opening Penalty for NRZ & RZ at 10 Gbps

<u>BER</u>

Figure 5.20 gives the variation of logarithm of BER as a function of propagation distance at data rate of 10 Gbps for the given input power (-10 dBm). BER for NRZ OOK format is lower than that of RZ OOK.

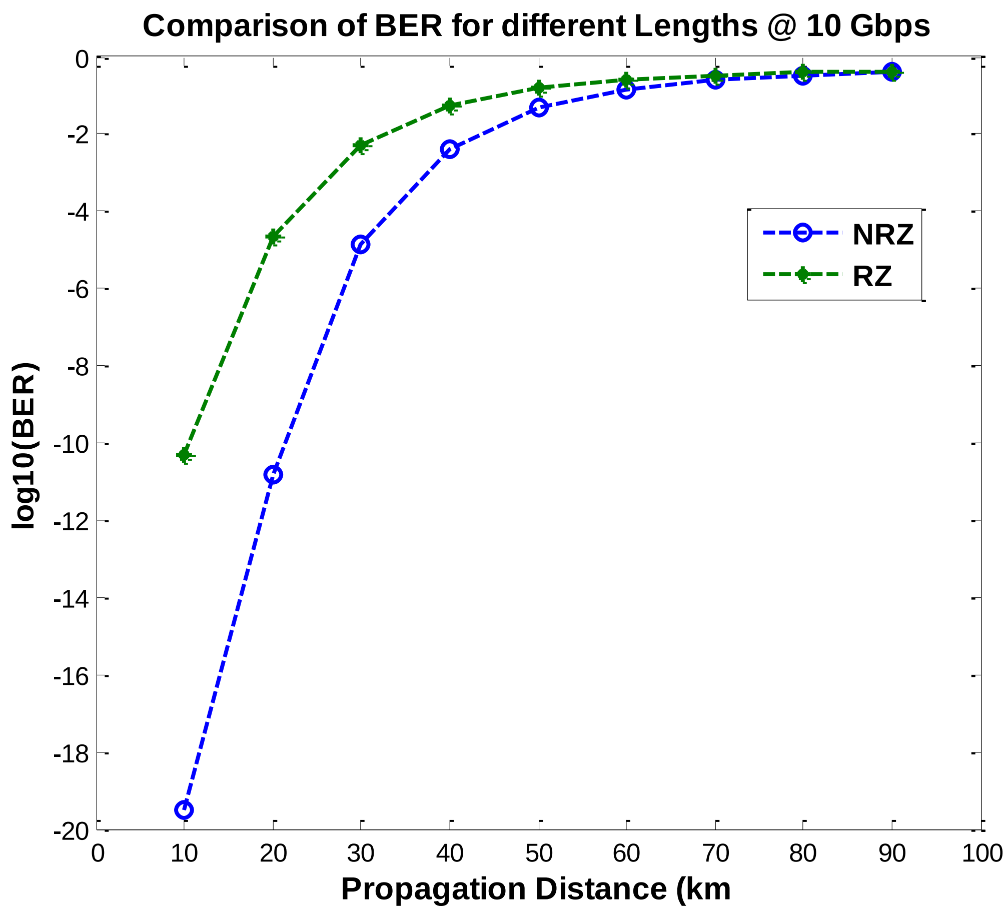

Figure 5.20 Log BER vs Lengths for NRZ & RZ at 10 Gbps

Figure 5.21 gives the variation of logarithm of BER as a function of input power for the data rate of 10 Gbps for given distance (80 km). BER for NRZ OOK format is lower than that of RZ OOK.

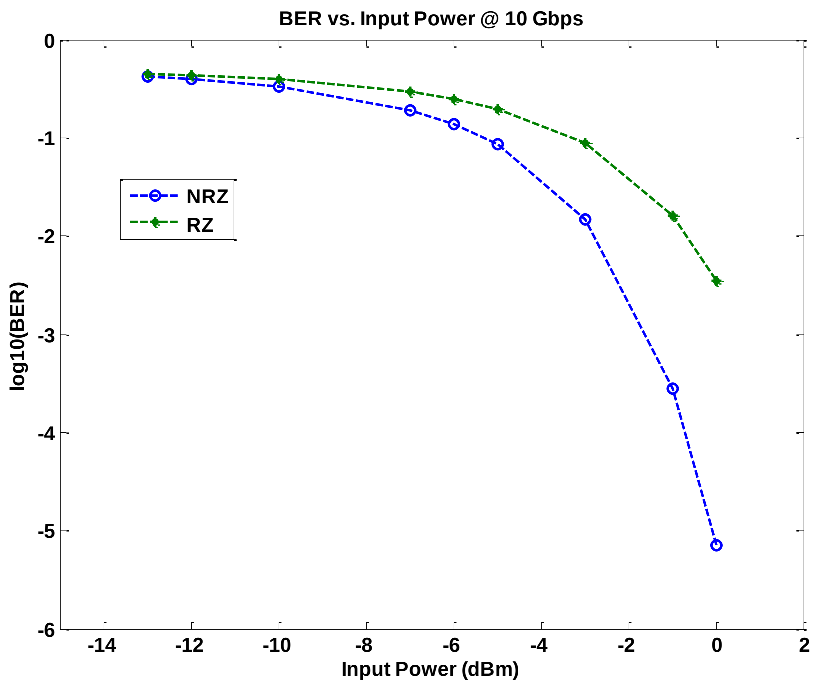

Figure 5.21 Log BER vs. Input Power level for NRZ & RZ at 10 Gbps

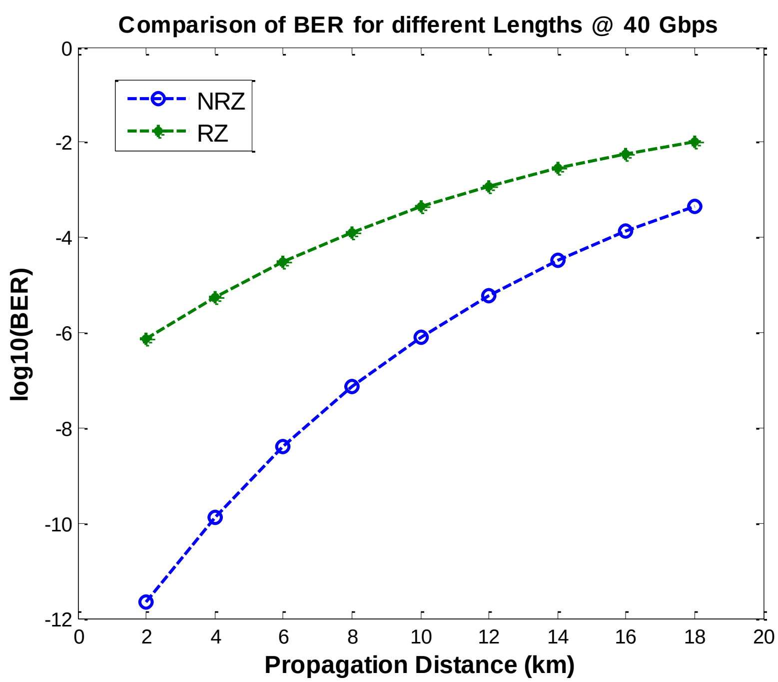

Figure 5.22 Log BER vs Lengths for NRZ & RZ at 40 Gbps

Figure 5.22 shown above gives the variation of logarithm of BER as a function of propagation distance at data rate of 40 Gbps for the given input power (-10 dBm). BER for NRZ OOK format is lower than that of RZ OOK

Figure 5.23 gives the variation of logarithm of BER as a function of input power for the data rate of 40 Gbps for given distance (20 km). BER for NRZ OOK format is lower than that of RZ OOK.

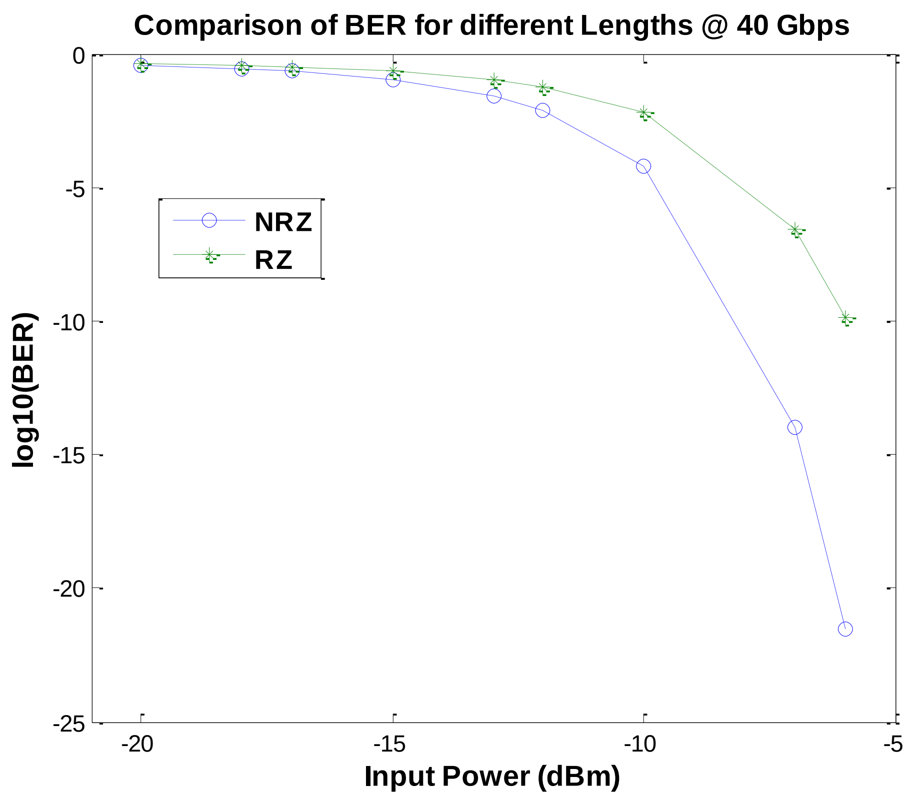

Figure 5.23 Log BER vs. Input Power level for NRZ & RZ at 40 Gbps

CHAPTER VI

Conclusion and Future Scope

This chapter concludes the dissertation work and also offers some future extensions to the work conducted.

6.1 Conclusion

.In this work performance analysis of basic data modulation formats that use direct detection is done. We covered NRZ OOK and RZ OOK formats for both 10 Gbps and 40 Gbps data rate

6.2 Future Scope

In future, further experimental and numerical analysis can be performed for investigating end-to-end over-all system performance for advanced modulation formats like DQPSK, QAM etc. Similarly we can investigate multi-level signals beyond two bits per symbol and other promising scheme like orthogonal frequency division multiplexing (OFDM). In OFDM, we utilize the orthogonality between the spectral profiles of each channel, and it can be very beneficial in future applications like optical wireless networks.

A.1 Appendix – MATLAB Code for NRZ OOK Simulation

```
% Study of NRZ Pulse propagation @ 10Gpbs  in a Repeaterless
Optical Link % E-field of the PBRS source is generated with bit
duration of 100ps % Rectangular NRZ signal (with zero rise time) is
passed through the filter which % models the rise time characteristics
of the external modulator.

clc;  clear all;

%%% SImulation Variables %%%

 D_parmeter = 17;        % ps/km-nm
 Power  =  -10;          % in dBm
 Dist = 10:10:90;        % propagation distance (in km)


%%%  Input Pulse Train Generation  %%

dt = 0.125*1e-12;                     % Time Sampling Rate
t_window = 100*1e-9;                  % Time Window  = 100ns
ns = 200*4;                           % No of pts in 1 bit duration
t = 0 : dt : t_window;  t(1)=[ ];     % Time Space;
N= round(t_window/(ns*dt));           % N = No of bits in time window;
 p = length(t);                       % Tot No of Samples

Rx_BW = 7e09;                         % Rx BW = 0.7*Bitrate

prbs_seed = [0 0 0 0 0 0 0 0 1];
 bit_dur = dt*ns;

 Amplitude   = sqrt(10^(Power/10)*1e-3);
 Y = Amplitude*ones(1,p);

% %% N bit PRBS Generation  %%%%

h = commsrc.pn('GenPoly', [9 5 0], 'InitialStates', prbs_seed, ...
        'CurrentStates', prbs_seed, 'Shift',  0, 'NumBitsOut', N);
  Prbs_gen = generate(h);       ;

%%%% Generation of NRZ-OOK PRBS Input Sequence  %%%%%
```

```
for j = 1:1:N
     n = (j-1)*ns;       % Data Modulation of CW signal with PRBS;
    Y(:,(n+1):(n+ns)) = Y(:,(n+1):(n+ns))*Prbs_gen(j);
end

  ip_seq = Y;

%%%% Filtering Operation at the Transmitter Side
( To model  finite rise time of the modulator driver circuit) %%%%%%

Wsm = (1/dt);                              % sampling frequency
Wip_cutoff = 2*pi*20e09;                   %  tr =15% of the bit period
[b,a] = besself(5,Wip_cutoff);
[num,den] = bilinear(b,a,Wsm);
ip_filtered = filter(num,den,ip_seq);
ip_seq = ip_filtered;

Op_Icurrfltr = zeros(p,length(Dist));
Op_Icurrfltr_Mean = zeros(1,length(Dist));

for i = 1:1:length(Dist)

Distance = Dist(i);

% %%%%%%% SSFT Simulation Block of SMF fiber  %%%%%

prop_length = Distance*1e03;
nz = 10;                       % nz = steps taken
dz = prop_length/nz;           % dz = smallest increment in total length (m)
D = D_parmeter*1e-06;          % ( s/m^2); Dispersion Parameter of a SMF.
beta2 =  -1.2745e-21*D;        % s^2/m; GVD parameter @1550nm
betap = [0, 0, beta2];         % beta vector input for ssprop function
alpha =  0.046*1e-03;          % alpha = 0.2 dB/km as Neper/meter

% Propagation through fiber.
op_fibr  = (ssprop((ip_seq'),dt,dz,nz,alpha,betap,0,50,1e-6))';
   % %  Modelling of Detector and Receiver and
          Addition of Gaussian random noise % %
```

```
 Op_Icurr = 0.9*op_fibr_int;      % Detector Responsivity  = 0.9 A/W;

  Op_Icurr =  Op_Icurr*400;       % Gain of Rx  = 400V/W;

 Noise_Eqv_Power = 25e-12*sqrt(Rx_BW);
% total noise power added at the Rx;

Op_Icurr = Op_Icurr+random('norm', 0, sqrt(Noise_Eqv_Power),1,p);

% %%%% Filtering  Operation at the Receiver Side %%%%%%

Wsm = 1/dt;                        % sampling frequency
Wop_cutoff = 2*pi*Rx_BW;      % 70% of the datarate for NRZ
[b1,a1] = besself(4,Wop_cutoff);
[num1,den1] = bilinear(b1,a1,Wsm);
Op_Icurr_fltr = filter(num1,den1,Op_Icurr);

Op_Icurrfltr(:,i) = Op_Icurr_fltr;

Op_Icurrfltr_Mean(:,i) = mean(Op_Icurr_fltr);

end


% %% To Study the Spectrum of Input & Output Sequence  %%

w = (-1*p/2:1:p/2-1)/(p*dt)/(1e9);      % Frequency Space(GHz);
ip_spectrum  = fftshift(fft(ip_seq))/p;
ip_spectrum = 10*log10(abs(ip_spectrum)/max(abs(ip_spectrum)));

figure;
plot(w,ip_spectrum);
xlabel(' Spectrum relative to optical center frequencey (GHz)');
ylabel('Power (dBm)');
xlim([-25 25]);    ylim([-45 0.1]);
title('Spectrum of NRZ OOK  @ 10Gbps');

 %  % Input Eye Digram  %%

  t_eye = (1:1:(3*ns))*dt;      % 3 bit duration for eye diagram
  q = (N-mod(N,3));
```

```
figure;
 for i=3:1:q/3
   m =(i-1)*3*ns;
   ip_seg = ip_intensity(:, m+1:1:m+3*ns);
   plot(t_eye,ip_seg);
   xlim([0 3*bit_dur]);
   ylim([1.1*min(ip_intensity) 1.1*max(ip_intensity)]);
   title({'Eye Diagram:','Input NRZ @10Gbps Transmitter Side'}) ;
   hold on;
 end


  figure;
 for k =1:1:length(Dist)

   Op = Op_Icurrfltr(:,k);
   subplot(3,3,k)

   for i=3:1:q/3
   m =(i-1)*3*ns;
    Op_Icurr_fltr_seg = Op(m+1:1:m+3*ns,:);
    plot(t_eye,Op_Icurr_fltr_seg);
   xlim([0 3*bit_dur]);
   ylim([min(Op_Icurrfltr(:,k))*1.1 max(Op_Icurrfltr(:,k))*1.1]);
   title(['L = ' num2str(Dist(k)) ' km'])
   hold on;
   end
end
```

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