Thesis Report

On

Simulation Analysis of PMD and Dispersion Mapping Techniques

Submitted in the partial fulfillment of requirement for the award of the degree of

MASTER OF ENGINEERING

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

Submitted by

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Last but not the least I would like to thank God for not letting me down at the time of crisis and showing me the silver lining in the dark clouds.

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **"Simulation Analysis of PMD and Dispersion Mapping Techniques,"** in partial fulfillment of the requirements for the award of degree of Master of Engineering in Electronics and Communications Engineering submitted in Electronics and Communications Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. R.S Kaler**. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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ABSTRACT

Optical fibers are not only used in the telecommunication but also used in the Internet and Local Area Networks (LAN) to achieve high signalling rates. Optical networks, based on the emergence of the optical layer in transport networks, provide higher capacity and reduced costs for new applications such as the Internet, video and multimedia interaction, and advanced digital services. But the linear and nonlinear characteristics of the fiber optical are the limiting factors to reach the goals. The objective of the thesis work is to investigate the limiting factors of the guided optical media.

In the standard single mode fibers, the Polarization Mode Dispersion is the phenomenon that causes the hurdles to reach the high bit-rate-distance product of amplified lightwave communication system. The impacts on eye opening, eye closing and output power due to PMD variation are studied. The impacts of PMD, in high data rate transmission systems have been investigated at different bit rates. It is reported that PMD produces the adverse effect on the eye opening, eye closing, and power at the output. Due to PMD, the significant degradation in the performance of high speed optical transmission system with the increasing bit rate is also reported. At the bit rate of 40 Gbps and above it is almost impossible to cope with PMD without the use of dispersion compensation.

The fiber nonlinear characteristics are the Optical Kerr effect and the stimulated scatterings. The fiber nonlinearities produce the input power limitations on the system as well as maximum transmission distance. To mitigate their effects, the dispersion mappings are used. Pre, post and hybrid or symmetrical compensation techniques are compared on the basis of bit error rate (BER) variation with the input power at higher bit rates. The dispersion compensation fiber (DCF) is used in the compensation techniques. It is demonstrated that the hybrid compensation is better to reduce the nonlinear effects than its counterparts. The increase in BER due to increase in the input power for all the three techniques is also reported.

Simulation results are presented to support the analysis PMD impacts and the comparison of compensation techniques.

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Twenty first century is the era of ‘Information technology’. There is no doubt that information technology has had an exponential growth through the modern telecommunication systems. Particularly, optical fiber communication plays a vital role in the development of high quality and high-speed telecommunication systems. Fiber optic communication is a way of exchanging the information between to places by sending the light signal through the optical fiber cable. Fiber optic communication brought the revolutionary change in the telecommunication industry and played a major role in the advent of information age. In the twenty first century, its advantages over electrical transmission cause the replacement of copper wire with the optical fiber in the communication system. Now the optical fiber is the most common type of channel used in communication system, but the other types of waveguides are also used within the communication system. Today, optical fibers are not only used in telecommunication links but also used in the Internet and local area networks (LAN) to achieve high signalling rates. The core advantages of optical fiber such as low loss, which allows long distances between amplifiers and its high data carrying capacity as that of thousands of electrical links would be required to carry that much data. Also no cross talk introduces in optical fibers running alongside each other for long distances as introduces in some types of electrical transmission lines.

The use and demand for optical fiber has grown tremendously and optical-fiber applications are numerous. Telecommunication applications are widespread, ranging from global networks to desktop computers. These involve the transmission of voice, data, or video over distances of less than a meter to hundreds of kilometers, using one of a few standard fiber designs in one of several cable designs [1].

But in the fiber optic communication system linear and nonlinear characteristics of fiber put limitations over high speed data transmission in the communication system. The Linear characteristics include attenuation, chromatic dispersion (CD), polarization mode dispersion (PMD), and optical signal-to-noise ratio (OSNR). The nonlinear characteristics include self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS). Nonlinear fibre effects such as self- and cross-phase modulation combined with the group velocity dispersion result in intensity distortion of the propagating signals in WDM links, limiting the maximum transmission distance. The transmission distances can be increased by optimising the dispersion map to reduce the impact of nonlinearities. Further the maximum transmission distance is limited by the dispersion or spreading of optical pulses as they travel along the fiber.

It was not until the advent of Erbium Doped Fiber Amplifier (EDFA) in the late 1980's [2], that chromatic dispersion in the fiber become main limiting factor in the optical transmission systems rather than fiber losses.

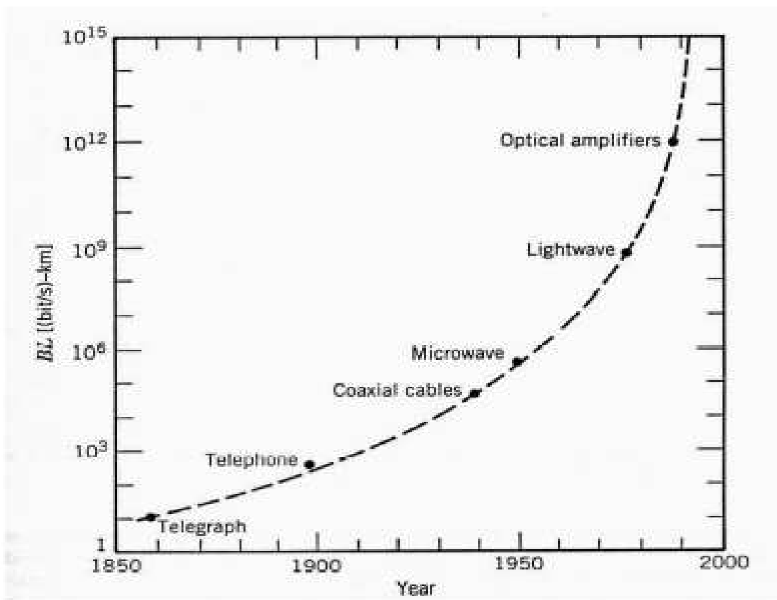

Figure 1.1: Increase in the bit rate –distance (B-L) product since 1850 [3]

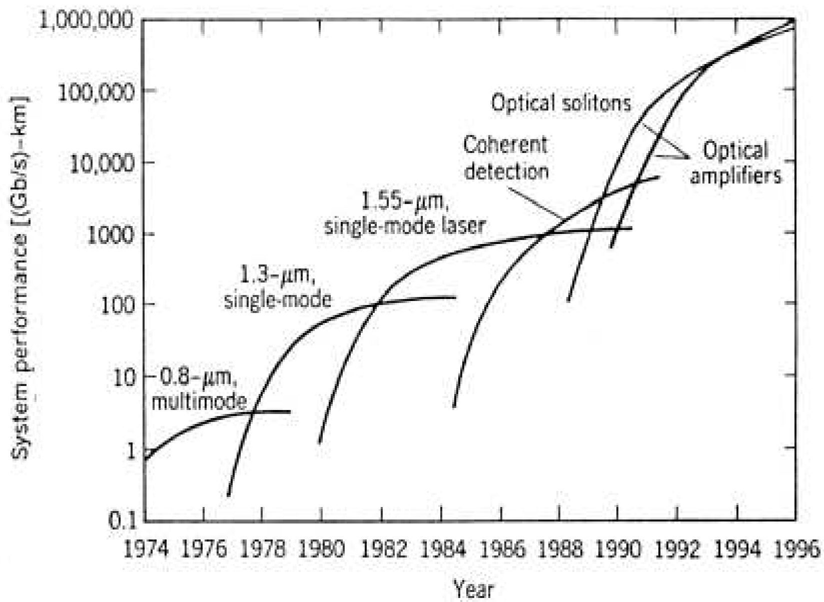

Figure 1.2: Progress in optical fiber communication since 1974

The mid 1980s saw telecommunication carriers like Sprint establish extensive fiber optic backbone networks. With the advent of the optical amplifier, or specifically the Erbium Doped Fiber Amplifier (EDFA) in 1986, it has been possible to increase the span and speed of optical fiber based communication operate, proved to be an important factor in fixing the wavelength of operation of present day fiber optic systems. Figure (1.1) shows the increase in the bit-rate distance product since 1850. Figure (1.2) depicts the growth of fiber-optic systems since 1974.

1.1 Polarization Mode Dispersion

The polarization related impairments have become a major obstacle to the increase transmission rates in WDM systems. Such impairments include polarization mode dispersion (PMD) in optical fibers, polarization dependent loss (PDL) in passive optical components, polarization dependent modulation (PDM) in electro optical modulators, and polarization dependent gain (PDG) in optical amplifiers.

Polarization Mode Dispersion, or PMD, is an important *linear* phenomenon occurring inside optical fibers, which can cause the optical receiver to be unable to interpret the signal correctly, and results in high bit error rates. PMD can dramatically decrease the fiber optic network's performance, particularly those networks operating at high data rates. The technology for years had been made a free ride as it grew from 90 Mbps to 270 Mbps to 435 Mbps to 2.5 Gbps [4]. A problem began to manifest itself in 5 Gbps systems and threatens major dislocation at 10 Gbps networking. For the first time, the fiber-optics industry was faced with a networking killer. It can distort signals, render bits inaccurate, and destroy the signal integrity of the network.

1.1.1 PMD Overview

While the phenomenon of Polarization Mode Dispersion (PMD) has been known for years, it has only been recently that it has posed a serious, realistic problem for optical networks. PMD's negative effects result in a limitation of a networks bandwidth or length that is, of course, undesirable to say the least. It is important to understand however, that with proper measurement and management, the negative effects of PMD may be minimized or eliminated altogether.

The older fibers had the PMD value 100 times greater than that of the present day fibers. But in the new fiber the PMD remains the major problem because of the following reasons:

i. There is still a small residual asymmetry in the fiber core as shown in figure (1.3).
ii. Slight PMD exists in the discrete in line components such as isolators, couplers, Erbium Doped Fibers, modulators and multiplexers.

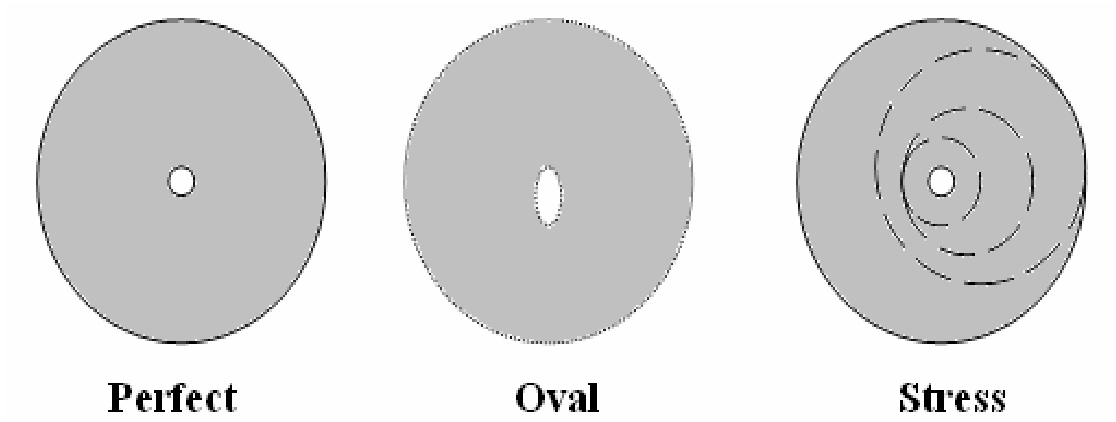

Figure 1.3: Cross-Sectional defects of Optical Fibers

In addition to this, internal forces induced by thermal expansion and external forces induced by the environment through handling and cabling, such as bending and twisting, add slight nonsymmetrical stress fields inside the fiber core. These deviations give rise to the phenomenon of birefringence. As a result of a property of optical fibers called ‘birefringence’, different polarizations of light are propagated at different velocities through the fiber. As laser light is generally highly polarized, the digital bits that they emit contain light that is also highly polarized. Couple this with the birefringence present in the fiber and the result is that different components (polarizations) of the digital bits travel at different velocities [5]. In other words some of the light in the bit travels faster and some of the light travels slower. This causes the digital bit to spread in time; this is termed dispersion. Moreover, the residual birefringence is not constant along the length of the fiber but changes with distance in a random way, not only in amount, but also in its local principal axes. So in the best conditions, PMD still significantly limits the deployment of high bit rate systems. For a given fiber, PMD is supposed to be fixed. However, this is not the case in real communication systems because environment fluctuations cause PMD to vary randomly in time. Therefore, it is important to understand the statistical properties of pulse propagation induced by PMD.

A single-mode fiber is designed to support only one mode of propagation of light. The principal advantage of letting light propagate along only one mode is that inter-modal dispersion can be avoided. Inter-modal dispersion happens as a result of relative delay between the light propagating in the various modes in a multi-mode fiber. In single-mode fibers, as there is only one mode available for light propagation (theoretically), inter-modal dispersion is nonexistent.

Single-mode optical fiber and components support one fundamental mode, which consists of two orthogonal polarization modes. This asymmetry introduces small refractive index differences for the two polarization states. This characteristic is known as *birefringence*. The birefringence causes one polarization mode to travel faster than the other, resulting in a difference in the propagation time, which is called the *differential group delay (DGD)*. DGD is the unit that is used to describe PMD. DGD is typically measured in picoseconds. A fiber that acquires birefringence causes a propagating pulse to lose the balance between the polarization components. This leads to a stage in which different polarization components travel at different velocities, creating a pulse spread as shown in Figure (1.4). PMD can be classified as first-order PMD, also known as DGD, and second-order PMD (SOPMD). The SOPMD results from dispersion that occurs because of the signal's wavelength dependence and spectral width. If the fibers were perfect, the state of polarization (SOP) of the light signal transmitting in the fiber would remain constant and the effects of the PMD, PDL, PDM, and PDG could be easily eliminated.

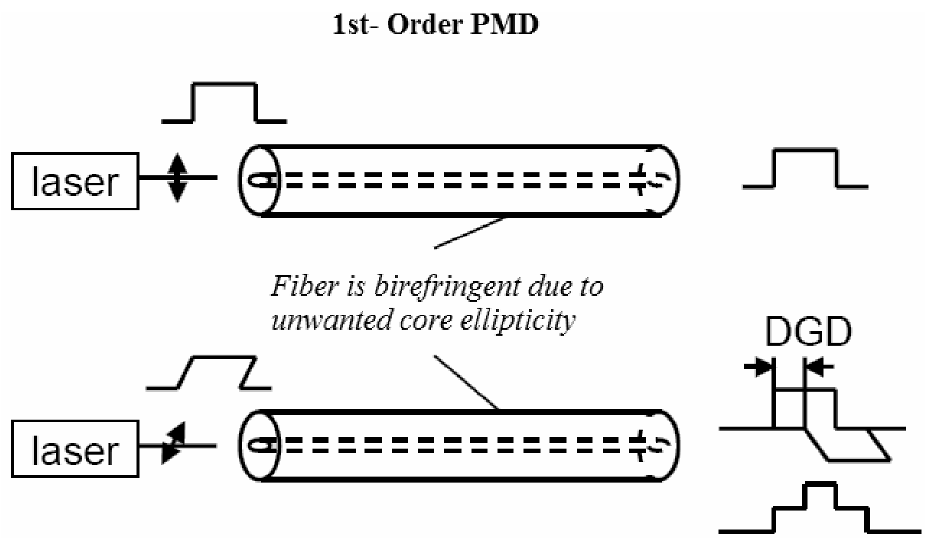

Figure 1.4: Polarization Mode Dispersion.

Unfortunately, the SOP of light propagating in the length of slandered communication fiber varies along the fiber due to random birefringence induced by the thermal stress, mechanical stress, and irregularities of the fiber core. Generally, at the output end of fiber the light polarized, with varying degrees of ellipticity, and with the major elliptical axis at the arbitrary angle. Worst of all, the induced birefringence changes with temperature, pressure, stress and other environmental variations, making polarization impairments time dependent.

The single mode fibers manufactured in mid 1990s have the property that has become more problematic as the bit rates and span lengths increases. This all was due to the imperfectly rounded fiber core. As the core of a fiber should have a perfect cylindrical shape, but in practice it is not possible to have ideally cylindrical shape because of change in core diameter randomly while drawing the fiber, so because of this physical limitation the PMD occurs [6]. So as it is impossible to manufacture the perfectly symmetrical and rounded fiber, the researchers got success to produce more symmetrically rounded fiber. But the problem of PMD still exists with a small coefficient of 0.1 $ps/\sqrt{km}$ [7].

1.1.1.1 Refractive Index

Light within a medium travels at a slower speed than in the vacuum. The speed at which light travels in the medium is determined by its refractive index. In an ideal situation, the refractive index would not depend on the wavelength of the light. However, this is not the case which results in different wavelengths travelling at different speeds within an optical fiber. Environmental conditions, such as variations in temperature can change the refractive index of the optical fiber. As temperature increases, so will the refractive index, however, the increase is not uniform over all wavelengths resulting in differing wavelength speeds. In addition, stress, such as the pressure experienced by a submarine cable, can affect the refractive index of an optical fiber. When pressure is exerted on the optical fiber the refractive index decreases. The amount of the decrease is also a function of the wavelength [8].

The refractive index of an optical fiber can have a different value across the horizontal and vertical axis of the fiber core. This difference in the refractive index results in the two orthogonal states of polarization (vertical and horizontal) travelling at different speeds through the fiber. The result is a Differential Group Delay, measured in $ps/\sqrt{km}$, between the two states of polarization (vertical and horizontal axis) and possibly intersymbol interference. This effect is known as Polarization Mode Dispersion (PMD). A typical design rule is that DGD should not exceed 10% of the bit rate for an NRZ signal. This implies that as the bit rate increases, the acceptable amount of DGD decreases. Meeting this design rule can be challenging since PMD is a result of geometric irregularities of the fiber core, temperature changes and stress placed on the fiber, making PMD unpredictable and statistical in nature.

1.1.1.2 Birefringence

The birefringence in optical fiber can be expressed as a difference in the refractive index, and hence propagation constant β, for the orthogonal polarization modes

$$\Delta\beta = \beta_s - \beta_f = \frac{\omega n_s}{c} - \frac{\omega n_f}{c} = \frac{\omega \Delta n}{c} = \frac{2\pi}{\lambda}\Delta n \qquad 1.1$$

Where ω is the angular frequency of the light, c is the speed of the light in vacuum and $\Delta n = n_s - n_f > 0$ is the refractive index difference between the slow and fast axis, while λ is the wavelength of the light in vacuum. The difference can also change the state of polarization (SOP) of the light as it travels along the fiber as illustrated in the figure (1.5). Two orthogonal polarization states exist (eigenstates) that are unaffected by the birefringence. Any polarization state can be decomposed into the two eigenstates. In the uniformly birefringent segment, the eigenstates corresponds to the well defined birefringence axes.

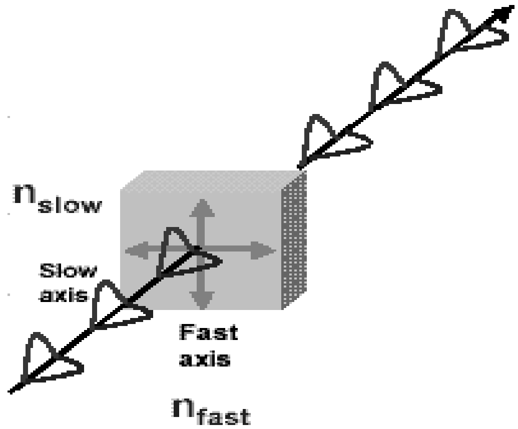

Figure 1.5: The local birefringence in an optical fiber changing the polarization state of the light.

The phase retardation between the two orthogonal fields due to birefringence causes the polarization to evolve in a periodic manner and the period of this variation is referred to as the beat length, $L_B = \frac{\lambda}{\Delta n}$**.** For standard single mode fiber Δn is typically 10^{-7} , which leads to a beat length to around 15 m at the wavelength 1550 nm. The difference in phase velocity indicated by equation 3.1 is usually accompanied by a difference in the local group velocity and by a subsequent splitting of pulses that travel through the fiber. This group velocity difference gives rise to a differential group velocity (DGD), Δt is a random variable that has a Maxwellian probability density function (pdf). Figure (1.5) shows the pulse splitting that arises due to the birefringence. In long fibers, the birefringence is combined with random polarization mode coupling and the PMD grows with the square root of the fiber length. The degeneracy can be lifted if, through a loss of the circular symmetry, any amount of anisotropy is introduced, leading to some birefringence [8, 9]. This is the general case of real fibers, where the loss of symmetry originates in the fiber manufacturing process from noncircular waveguide geometry (geometrical birefringence static) or in deployed fiber from non symmetrically distributed mechanical stress (stress birefringence time varying) [10].

1.1.2 How PMD Occurs

When light travels down a single mode fiber toward the receiver, it has two polarization modes that follow the path of two axes. They move toward the receiver at right angles to each other. When the core of the fiber that bounds the light is asymmetrical, the light travelling along one polarization axis moves slower or faster than the light polarized along the other axis. This effect can spread the pulse enough to make it overlap with other pulses or change its own shape enough to make it undetectable at the receiver as shown in figure (1.6).

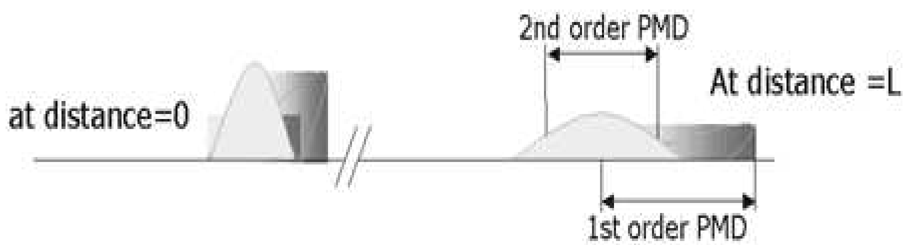

Figure 1.6: Occurrence of PMD at distance L

As figure (1.6) shows, the optical pulse and its constituent photons travel from the source, or transmitter, at distance 0, along the single-mode optical fiber. At some distance after PMD has affected the pulse, the polarized energy is separated by some time. This time is known as differential group delay (DGD). DGD is the fundamental measure of PMD and is measured in picoseconds (10-12 seconds). If DGD is severe, the receiver at some distance *L* cannot accurately decode the optical pulse, and bit errors can result. The optical eye pattern of a PMD-limited signal exhibits the effects of DGD by “closure” of the eye. The effect of the eye closure is caused by the separation of the polarized axes of photons, as the DGD becomes higher, separation becomes greater, and optical pulses start to interfere with each other.

PMD is not an issue at low bit rates but becomes an issue at bit rates in excess of 5 Gbps. PMD is noticeable at high bit rates and is a significant source of impairment for ultra-long-haul systems. PMD compensation can be achieved by using PMD compensators that contain dispersion-maintaining fibers with degrees of birefringence in them. The introduced birefringence negates the effects of PMD over a length of transmission. For error-free transmission, PMD compensation is a useful technique for long-haul and metropolitan-area networks running at bit rates greater than 10 Gbps. The PMD value of the fiber is the mean value over time or frequency of the DGD and is represented as $ps/\sqrt{km}$. A 0.5-dB power margin is typically reserved to account for the effects of PMD at high bit rates.

1.1.3 Pulse Broadening due to PMD

It is relatively easy to determine the pulse broadening/ splitting that occurs as an effect of pure first order PMD. Some investigations have been made on pulse broadening due to lower- order PMD (first and second) [11]. However, an explicit formula for the RMS broadening of pulses affected by (all-order) PMD was recently derived [12]. The output pulse width (in the absence of chromatic dispersion) is given by

$$\tau^2 = \tau_0^2 + \frac{1}{4}\left(\langle\Omega^2\rangle - [s.\langle\Omega\rangle]^2\right) \qquad 1.2$$

Where τ is RMS intensity pulse width, s is the input polarization state in stokes space, f(t) is the initial amplitude and f(ω) is the Fourier transform as defined as $f(\omega) = \int_{-\infty}^{\infty} f(t)\exp(-i\omega t)d\omega.$ The bracket notation shows the over normalized pulse spectrum so that $(a) = \frac{1}{2\pi}\int a|f(\omega)|^2 d\omega = a$, if a is constant. To apply this formula the measure DGD and PSP, is integrated over the pulse spectrum. In the special case of pure first order PMD, the PMD is constant, $\Omega = \Delta\tau\Omega$ and the pulse broadening is given by

$$\tau^2 = \tau_0^2 + \frac{\Delta\tau^2}{4}\left(1 - (s..\Omega)^2\right) \qquad 1.3$$

The maximum broadening is obtained if the pulse is launched between the PSPs (principle state of polarization) so that $s.\Omega = 0$, while no broadening occurs when $s.\Omega = \pm 1$, which corresponds to launching the pulse into the PSP. The expected pulse broadening in the presence of an average PMD can also be determined by calculating the expected value.

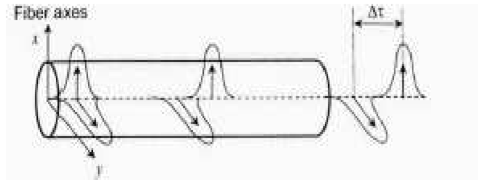

Figure 1.7: A pulse separation into x and y axis due to DGD at the output [13].

As mentioned earlier, since all telecommunication grade fibers fall in the "long" fiber category, it is necessary to bring out their differences from the "short" fibers. The relation between PMD induced delay and fiber length is no longer linear in the case of long fibers. This is because of the phenomenon called mode coupling that is taking place in all fibers longer than a certain statistical length called correlation length or coupling length. Fibers that are shorter than the correlation length are considered to belong to the "short" fiber category and all the other fibers are considered to belong to the "long" fiber category. As a light wave propagates down a fiber, there is a constant sharing of energies between the two propagating modes as shown in figure (1.7). This random exchange of energies is due to the varying stresses or perturbations that are experienced by the fiber along its length.

The effect of mode coupling is that the DGD has a square root of length dependence rather than linear length dependence. However, in either case, PMD causes dispersion or broadening of the light wave signal. This broadening is predictable in the case of short length fibers. The relation that gives an estimate of the PMD induced limitation on the bit rate and the span of a digital fiber-optic system is [14]:

$$B^2 L = \frac{0.02}{(PMD)^2} \qquad 1.4$$

Where, B and L are the bit rate (Gbps) and link length (km), respectively and PMD units are $ps/\sqrt{km}$ .This relation was arrived at by considering the case that the PMD induced delay must be less than 14% of the bit period in order to avoid incurring PMD-induced power penalty of 1 dB or greater for a period of 30 min per year [14]. Figure (1.8) shows the bit error fluctuations due to the variable nature of PMD and the influence of temperature on its variability.

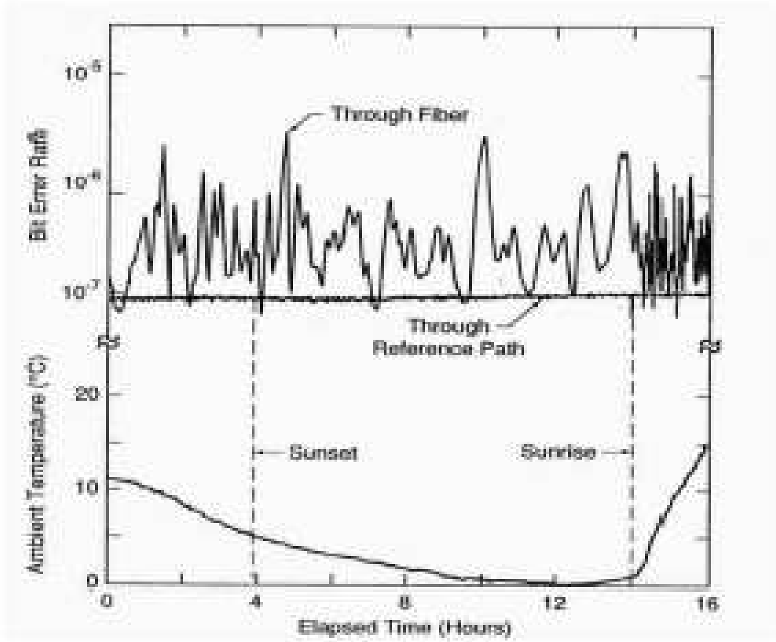

Figure 1.8: Measured bit error rate fluctuations due to PMD with the rate of change of ambient temperature.

1.1.4 PMD Characterization

There are two parameters that characterize the PMD: principal states of polarization and differential group delay. Signals oscillate through fiber along two planes at right angles to each other, called the principal states of polarization. For a fixed PMD, DGD is a random variable that has a Maxwellian probability density function (pdf). In a PMD free fiber, polarization states do not change and the energy in each state arrives at the receiver at the same time. In the presence of PMD, however, the states change and the arrival time of one state varies with respect to arrival time of the other. This time difference is Differential Group Delay (DGD). Since asymmetry causes PMD, DGD increases with both the fiber's PMD coefficient and its length. At some distance PMD effects become so great that regeneration is necessary unless the effect of PMD is mitigated. To find the "peak value" typically multiply the statistical average DGD. That is the value above which less than 1% of delay values are likely to exist. Regeneration distance is inversely proportional to the square root of the channel rate.

For a length of fiber, at every frequency, there is a pair of input polarization states called the PSPs. A PSP is that input polarization state for which the output state of polarization is independent of frequency over a small frequency range. Using the PSP concept, PMD can be characterized as a vector represented as [15]:

$$\vec{\tau} = \Delta\tau\hat{P} \qquad 1.5$$

The PMD vector is a vector in three-dimensional spaces (Stokes space). The length of the vector ($\Delta\tau$) is the DGD and the direction of the vector ($\hat{P}$) is along the axis that joins the two output PSP points in Stokes space [15, 16].

Excellent reviews are available [17], covering the practical aspects and applications of PMD concepts to fiber transmission systems and the effects of PMD on nonlinear fiber transmission. In this review we aim to complement these surveys and to collect and synthesize the fundamental concepts and theory of PMD. PMD can cause several undesirable effects that could be obstacles to high speed telecommunication through optical fibers. Such effects are not limited to digital communication systems but affect analog communication systems as well. With the evolution of specialized manufacturing methods, PMD in present day, telecommunication grade fibers is kept very low ($< 0.1\, ps/\sqrt{km}$). Still no matter how good the fiber may be, at some bit-rate-length product, PMD will be an issue.

1.2 Dispersion Mapping

The advent of optical repeaters based on erbium-doped fiber amplifiers (EDFAs) has opened the new era of optical transmission technologies, allowing us to use wavelength-division- multiplexing (WDM) technologies with simple, compact, and economical approaches [18]. In fact, the demonstrated capacity for long-haul optical transmission has been growing remarkably, and more than a thousand fold increase in capacity has been achieved over the past ten years. The price we have to pay for such success is the combat with the accumulated impact of fiber nonlinearity, interplaying with the chromatic dispersion of the transmission fiber, which grows with transmission distance and, therefore, becomes significant for ultra-long-haul systems. Dispersion-management technologies have been invented to overcome such inherent problems in optically amplified transmission systems [19].

The transmission of optical signals in an optical communication system may be limited by optical effects such as chromatic dispersion. Optical signals may be transmitted as pulses of light in an optical fiber. When light propagating within an optical fiber undergoes chromatic dispersion, the light is delayed within the optical fiber. The delay causes spreading of the light pulses, which may affect the performance of the system. The specific amount of dispersion that an optical signal undergoes varies depending upon the wavelength of the optical signal. The extent to which dispersion varies as a function of light wavelength is often referred to as dispersion slope. Various dispersion management techniques have been used to reduce dispersion and to manage dispersion slope by reducing dispersion at individual channel wavelengths. Dispersion management is particularly important in wavelength division multiplexed (WDM) optical communication systems transmitting multiple channels at multiple wavelengths.

Dispersion can be minimized when the signals are placed symmetrically around the fiber's zero-dispersion wavelength $\lambda_D = 0$, but then FWM will increase and severely degrade system performance. Since higher dispersion will eliminate FWM, therefore, two solutions to suppress FWM include: 1) placing all wavelengths away from, and on only one side of $\lambda_D = 0$; and 2) utilizing alternating fiber segments with positive and negative dispersion values in a dispersion-managed system in which there is always an absolute dispersion value exists along the link, but the total accumulated dispersion is 0. In both these cases, each WDM channel accumulates a different amount of dispersion because of the spectrally dependent dispersion slope of the fibers. Additionally, each channel experiences SPM/XPM which interacts with the GVD, resulting in further degradation. To combat dispersion and nonlinearities, each WDM channel can separately be either pre-compensated, post-compensated or dual-compensated (using a combination of pre- and post-compensation) in total accumulated dispersion [20].

1.2.1 Origins of Nonlinearities

When radiation is incident upon a medium, the oscillating electromagnetic field interacts with electric dipoles in the molecules of the medium and causes them to oscillate. The result is a time-varying local electric polarization in the medium. This oscillating electric field then re-radiates the electromagnetic field and the incident wave is considered to propagate through the medium via a series of such absorption and re-radiation processes. The polarization vector **P**, induced by an electric field with amplitude vector **E** can be expressed as a general series expansion of the form [21]

$$P = \varepsilon_0 \left(\chi . E + \chi_2 : EE + \chi_3 \vdots EEE + ... \right) \qquad 1.7$$

ε_0 is the electric permeability of a vacuum,

χ is the linear susceptibility tensor of the medium and

χ_2 *and* χ_3 are second and third order susceptibility tensor terms.

If the induced polarization has a purely linear dependence on the applied electric field then the re-radiated electric field will be identical to the incident field. However, when second or higher-order susceptibility terms are nonzero, harmonics begin to appear in the radiated field that was not present in the incident field. For materials that have a symmetrical molecular structure, the polarisation induced by an incident electric field is symmetrical, as illustrated in figure (1.9). The susceptibility of these materials contains only odd expansion terms, as opposed to anti-symmetric molecules for which even terms such as may be non-zero.

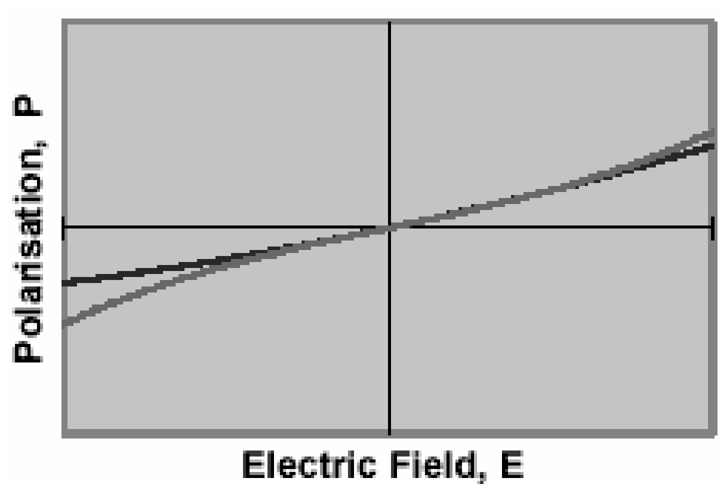

Figure 1.9 Electric polarisation versus electric field for materials with inversion symmetry (broken line) and with asymmetric molecular structure (Solid dark line).

The dominant susceptibility term is the linear term, χ which determines the linear refractive index of the medium, *n*, and the absorption attenuation coefficient α . The orders of the non-zero expansion terms determine the type of non-linearity to which the medium is susceptible. In materials, which lack a center of symmetry, such as quartz, KDP and ADP, the second order susceptibility is responsible for *second harmonic generation* [22], in which an intense wave at angular frequency ω_1 generates another wave at twice this frequency, $2\omega_1$. Another effect which is possible in these materials is *sumfrequency generation*; in which two waves at ω_1 *and* ω_2 interact to produce waves at $\omega_1 + \omega_2, 2\omega_1 + \omega_2, 2\omega_2 + \omega_1$.

1.2.2 Optical Kerr Effect

The optical Kerr effect or AC Kerr effect is the case in which the electric field is due to the light itself. This causes a variation in index of refraction which is proportional to the local irradiance of the light. This refractive index variation is responsible for the nonlinear optical effects of self-focusing and self-phase modulation. This effect only becomes significant with very intense beams such as those from lasers. In fact, phase modulation due to intensity dependent refractive index induces various nonlinear effects, namely, self-phase modulation (SPM), cross-phase modulation (CPM), and four-wave mixing (FWM).

1.2.2.1 Self Phase Modulation (SPM)

Phase modulation of an optical signal by itself is known as *self-phase modulation (SPM)*. SPM is primarily due to the self-modulation of the pulses. Generally, SPM occurs in single-wavelength systems. At high bit rates however, SPM tends to cancel dispersion. However, consideration must be given to receiver saturation and to nonlinear effects such as SPM, which occurs with high signal levels. SPM results in phase shift and a nonlinear pulse spread. As the pulses spread, they tend to overlap and are no longer distinguishable by the receiver. The acceptable norm in system design to counter the SPM effect is to take into account a power penalty that can be assumed equal to the negative effect posed by XPM. By the SPM-impact new spectral components are generated in the optical signal spectrum resulting in a spectral broadening.

1.2.2.2 Cross Phase Modulation (XPM)

Cross-phase modulation (XPM) is a nonlinear effect that limits system performance in wavelength Division Multiplexed (WDM) systems. XPM is the phase modulation of a signal caused by an adjacent signal within the same fiber. XPM is related to the combination (dispersion/effective area). XPM results from the different carrier frequencies of independent channels, including the associated phase shifts on one another. The induced phase shift is due to the *walkover* effect, whereby two pulses at different bit rates or with different group velocities walk across each other. As a result, the slower pulse sees the walkover and induces a phase shift. The total phase shift depends on the net power of all the channels and on the bit output of the channels. Maximum phase shift is produced when bits belonging to high-powered adjacent channels walk across each other.

1.2.2.3 Four Wave Mixing (FWM)

FWM can be compared to the intermodulation distortion in standard electrical systems. When three wavelengths (λ1, λ 2, and λ 3) interact in a nonlinear medium, they give rise to a fourth wavelength (λ 4), which is formed by the scattering of the three incident photons, producing the fourth photon. This effect is known as *four-wave mixing (FWM)* and is a fiber-optic characteristic that affects WDM systems. The effects of FWM are pronounced with decreased channel spacing of wavelengths and at high signal power levels. High chromatic dispersion also increases FWM effects. FWM also causes interchannel cross-talk effects for equally spaced WDM channels.

1.2.2.4 Stimulated Scattering

When light is incident on material it undergoes various scattering process. Most of the scattering is elastic, and the scattered wave has the same frequency as the incident wave. However, this scattered light is, in general, at some arbitrary angle to the forward direction of propagation. Hence, if one measures the transmitted light in the forward direction, there is a reduction in intensity as a result of the scattering into other directions. This loss is known as Rayleigh scattering loss. The frequency shifts can be small (approximately 1 cm-1) or large (greater than 100 cm-1). When the frequency shift is small, the process is known as Brillouin scattering. The larger frequency shifts characterize the regime of Raman scattering.

Stimulated Brillouin scattering (SBS) is due to the acoustic properties of photon interaction with the medium. When light propagates through a medium, the photons interact with silica molecules during propagation. The photons also interact with themselves and cause scattering effects such as SBS in the reverse direction of propagation along the fiber. In SBS, a low-wavelength wave called *Stoke's wave* is generated due to the scattering of energy. This wave amplifies the higher wavelengths. The gain obtained by using such a wave forms the basis of Brillouin amplification. The Brillouin gain peaks in a narrow peak near the C-band. SBS is pronounced at high bit rates and high power levels.

The SRS refers to lower wavelengths pumping up the amplitude of higher wavelengths, which results in the higher wavelengths suppressing signals from the lower wavelengths. One way to mitigate the effects of SRS is to lower the input power. In SRS, a low-wavelength wave called *Stoke's wave* is generated due to the scattering of energy. This wave amplifies the higher wavelengths. The gain obtained by using such a wave forms the basis of Raman amplification. The Raman gain can extend most of the operating band (C- and L-band) for WDM networks. SRS is pronounced at high bit rates and high power levels.

1.2.3 Dispersion compensation in optical transmission lines

Depending on the place and realization where the dispersion compensation is made in a system, it can be distinguished between three compensating methods: a) pre-chirp techniques at the transmitter side b) dispersion compensation in the transmission line (in-line compensation) and c) dispersion compensation at the receiver side (Fig. 1.10).

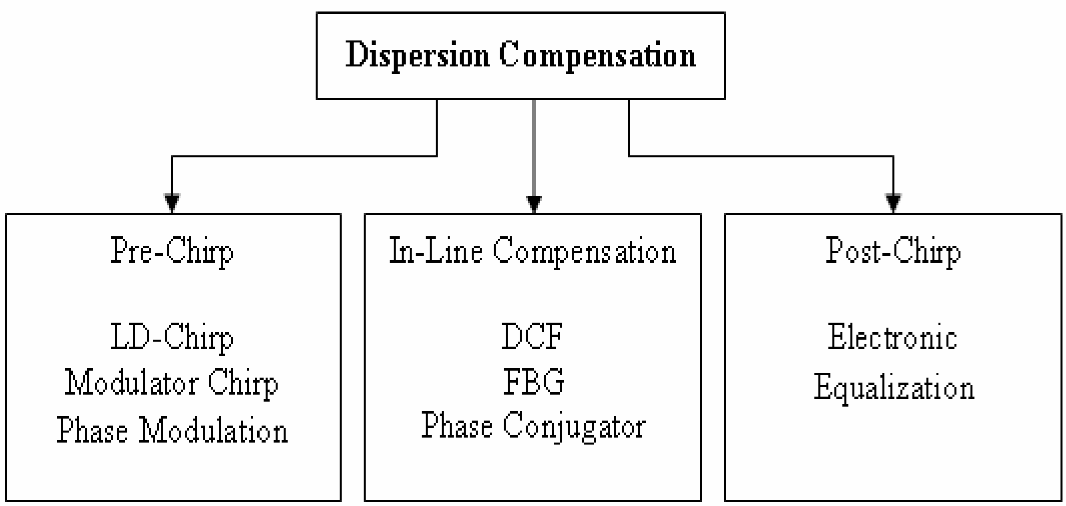

Figure 1.10: Dispersion compensation methods

The idea behind the pre-chirping at the transmitter side is the implementation of chirp with the opposite sign to the fiber chirp in order to counter the GVD effects in the fiber. The main implementation area of this technique is cost effective, optical short-reach systems (e.g. MANs) with smaller channel bit rates, but in combination with other dispersion compensation techniques (e.g. in-line compensation) it can enable a performance improvement even in high-bit rate transmission systems over long distances [23]. In-line dispersion compensation represents the key enabling technology for the realization of long-haul transmission systems. The dispersion compensation is realized in the optical domain without electro-optical conversion of the signal, enabling better compensation of the signal because the optical phase is maintained. The post-chirp techniques at the receiver side are characterized by the compensation of the chromatic dispersion in electrical domain. This compensation method is cost effective, and in combination with in-line compensation, enables an enhanced transmission performance.

1.2.3.1 In-line Compensation Devices

Implementation of in-line compensation devices in the transmission line affects the transmission performance of the system because of the interaction of dispersion map with transmission disturbances (e.g. ASE-noise, nonlinearities). The following dispersion compensating devices are used for the realization of in-line dispersion compensation:

Dispersion Compensating Fiber (DCF) represents the most widely used in-line dispersion compensation technique in today's transmission systems. The DCFs are characterized by a large negative dispersion and a small core diameter. The large negative dispersion values can be achieved by variation of the fiber profile by doping the fiber cladding (e.g. by fluorine), introducing an increase in the refractive index difference between the core and cladding. The demands on DCFs are a large negative dispersion (-70-300 ps/nm), low insertion losses, low polarization dependent (PDL) losses, a low polarization mode dispersion (< $\sqrt{0.05}$ ps/km), a large effective area (A_{eff}) and a negative dispersion slope. The DCFs can be used for simultaneous compensation of several channels, but due to imperfections in slope compensation, a small amount of residual dispersion remains especially in outer channels.

Fiber Bragg Grating (FBG) modules are fabricated by implementing refractive index changes in the fiber core. The regions with different refractive indices are called gratings. Depending on the distance between the gratings known as grating period, which can be realized as constant or varying (chirped), the shorter wavelengths will be reflected before the longer ones. The consequence is pulse compression and dispersion compensation. FBGs represent a promising technology for the realization of dynamic dispersion compensation in tuneable dispersion compensators. The advantages of FBGs are large nonlinear tolerance and lower device loss. The main FBG drawback is an increased device complexity because of the implementation of optical circulators and large ripples in insertion losses (IL) and group delay (GD).

Phase Conjugator is utilizes the concept known as mid-span spectral inversion (MSSI). The principle of MSSI is the spectral inversion of the optical signal spectrum in the middle of the transmission span by applying an active component (e.g. semiconductor laser) or highly nonlinear fiber (e.g. nonlinear phase-conjugating mirror). The short wavelengths of the signal are interchanged with the longer wavelengths making use of a nonlinearity based phase conjugation. This concept enables a full compensation of dispersion and dispersion slope, but it is less practical for the implementation in the transmission systems because of its complexity.

For the system used in this work, conventional DCF based compensation devices are implemented because of the fact that they represent the state-of-the-art technology in today's optical communication systems.

1.2.3.2 Dispersion compensating schemes

Depending on the placement and the combination of in-line compensation devices in the transmission line, several different dispersion compensation schemes can be realized (Fig. 4.2). Common for all dispersion compensation schemes enabling the full dispersion compensation is that the compensation of the accumulated dispersion in the transmission fiber has to be performed according to the following rule:

$$D_{SMF} \, . L_{SMF} + D_{DCF} \, . L_{DCF} = 0 \qquad 1.8$$

Where, D_{SMF} , D_{DCF} are the chromatic dispersion values of transmission and compensating fibers, respectively, and L_{SMF} , L_{DCF} the lengths of these fibers. This rule can be fulfilled by placing DCFs in different positions within a transmission line. Typically, a transmission line consists of several cascaded spans. Depending on the realization of the span infrastructure, it can be distinguished between three basic dispersion compensation schemes: pre, hybrid and post-compensation figure (1.11). In pre- and post-compensation the DCFs are placed before or after the SMF fiber. In hybrid-compensation 50% of the SMF dispersion is compensated before the SMF and the other 50% is compensated afterwards. The system behaviour can be quite different for the different schemes because of the influence of dispersion compensation on the linear and nonlinear effects. This influence varies for different channel data rates making a system upgrade becoming a critical issue.

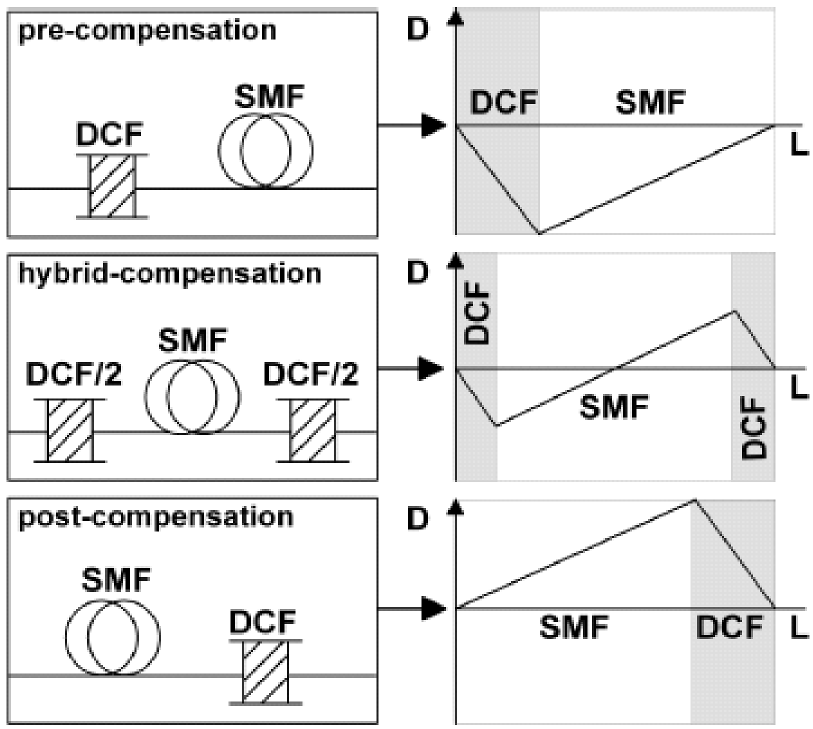

Figure 1.11: Principles of dispersion compensation

The full dispersion post-compensation scheme provides full compensation and signal shape regeneration after each span. This scheme is interesting for the practical implementation because the optical signal form is maintained after each span and the signal can be easily accessed or detected. The nonlinear characteristics of this scheme are rather poor, because the walk-off between adjacent channels in the system vanishes after each span resulting in an increased impact and accumulation of inter-channel nonlinearities (e.g. XPM), depending on the local dispersion of the transmission fiber. The nonlinear tolerance of this scheme can be improved by implementation of the pre-chirp at the transmitter side [23]. A similar effect can be achieved by pre-compensation (under-compensation) of chromatic dispersion along the transmission line. Depending on the amount of under-compensation, the accumulated residual dispersion varies from span to span. The drawback of this approach is the necessity of additional or tuneable dispersion compensation at the end or within the transmission line, if some channel has to be dropped or switched. This can be critical in systems with higher channel bit rates (>10Gbps) because of a reduced dispersion tolerance. A more exotic compensation scheme, are known as compact dispersion compensation or hybrid-compensation where dispersion compensation of the total accumulated system dispersion is realized directly after the transmitter and before the receiver. The advantage of this approach is that the impact of nonlinearities in the transmission line can be significantly suppressed, because the pulses are fully dispersed during propagation. This scheme is less relevant for the practical implementation, because the optical channels cannot be accessed within the transmission line.

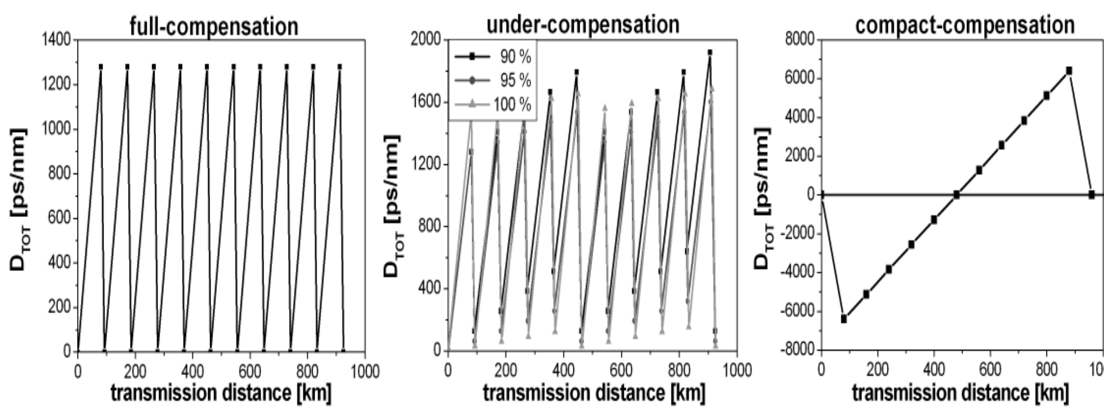

Figure 1.12: Dispersion compensation schemes in multi-span systems

The compensation of only β_2 (chromatic dispersion) alone is insufficient for the compensation of accumulated dispersion in high speed transmission systems, because of the existence of dispersion slope, which results in a wavelength dependent residual dispersion. Theoretically, the complete slope compensation could be realized if the DCF slope (S_{DCF}) can be tailored to:

$$S_{SMF} . L_{SMF} + S_{DCF} . L_{DCF} = 0 \qquad 1.9$$

The fiber nonlinearities like SBS (Stimulated Brillouin Scattering) and SRS (Stimulated Raman Scattering) also put the limitation on the input power up to a threshold value. Because the optical waveguides do not always behave as completely linear channel whose increase in output optical power is directly proportional to the input optical power [9]. The nonlinearities produces the effects which in case of scattering cause disproportionate attenuation, usually at high power levels. This effect causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence become significant above threshold power levels. It causes the distortion in the information with increase in input power.

1.3 Thesis Objective

In optical communication systems, the input signal to the fiber is usually a composite optical signal modulated with information bit streams. When the entire input signal frequencies interact with the effects caused by fiber linear (PMD) and nonlinear (Kerr Effects) characteristics, the output bit stream may behave in a complicated way giving adverse effects on system performance. Polarization Mode Dispersion represents the key limitation on the transmission speed of the system. Fiber nonlinearities represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single optic fiber. **The key objective of this thesis is**

1. **To study the effects of the variation of PMD on the system performance in terms of eye opening, eye closing and output optical spectrum.**
2. **To analyze the effects of PMD on the high speed transmission and with the variation of link length of the optical systems with the help of eye diagrams.**
3. **To compare the different dispersion mapping techniques.**

First the theoretical background is discussed on how the PMD and fiber nonlinearities affect system performance of an optical fiber communication system, also discussed the affects of the above two on the present day high speed communication systems.

1.4 Thesis Organization

This chapter includes the brief introduction to the optical communication with brief history. In this PMD and Kerr effect due to fiber nonlinearities are discussed in brief. The **Second chapter** contains the literature survey of effects of PMD and fiber nonlinearities on optical communication. Further the techniques used by various authors for the nonlinear dispersion compensation, are also discussed. In the **third chapter,** the effects of PMD variation are studied with the help of eye diagrams, optical spectrum and power output. The **fourth chapter** contains the study of the PMD impacts on communication system at higher bit rates. The impacts are studied with the help of eye diagrams at different bit rates and link lengths. The **fifth chapter** gives the comparison study of the dispersion mapping techniques to compensate fiber nonlinear effects. Comparison is done on the basis of variation of BER (Bit Error Rate) with input power of the system. Finally the **sixth chapter** gives the conclusion of the thesis work.

The polarization related and nonlinear impairments have become a major obstacle to increase the transmission rates in WDM systems. The work done by different authors is reviewed is given below.

2.1 Polarisation Mode Dispersion

G.J. Foschini and C. D. Poole [24] gave their ideas towards the small deviations from perfect circular symmetry in the core region of single mode fibers cause the optical pulses to become broadened as they propagate and causes intersymbol interference. They had also identified the three dimensional polarization vectors and characterize the polarization effects in narrowband sources. They specify the solution of Poole's stochastic dynamical equation for the evaluation of the polarization dispersion vector with fiber length. Their work represented a close interplay of theory with experiment and simulation. They determined the properties of the three components of the dispersion vector, probability density of the components of the derivative of the dispersion vector, relative strength of the first order and second order effects and the square root of the fiber length dependence on the magnitude of the dispersion vector.

Daniel Mahgerefteh, Curtis R. Menyuk [25] dealt with the effect of first order PMD compensation on pulse broadening in the fiber with randomly varying birefringence. They had shown the demand of bandwidth of higher bit rates in older installed fibers where PMD is a limiting factor. PMD in standard telecommunication fibers can be compensated to first order by using the concept of principle state of polarization. At the receiver the pulse is decomposed into two waveforms polarized along the two principle states for the optical link and their delay is removed. Compensation sharpens the probability distribution function of the pulse duration by a factor that decreases with increasing polarization dispersion. They also shows that the small randomly varying birefringence of fibers tends to depolarize optical signals and randomize their phase.

M. Wegmuller, S. Demma, C. Vinegoni and N. Gisin [26] analyzed the impact of first and second order polarization mode dispersion, they also found that the principal states vectors can lead to important fluctuations around the mean penalties induced by the first order PMD. They found that the approaches which try to mimic a standard fiber as closely as possible; the emulator presented gives constant but user adjustable values for differential group delay (DGD) and the ratio of first to second order PMD. Once it is set, the ratio is conserved while the DGD can be easily varied within the range of 0-300 ps. This allows investigating the low probability events of large DGD and second order PMD important for system outage.

According to the paper given in [27], Ling-Wei Guo, Ying-Wu Zhou, Zu-Jie Fang gave their ideas towards the pulse broadening of optical signals in a single mode fiber was studied theoretically in presence of PMD, PDL, Chromatic dispersion and spectral chirping. Analytical expressions were derived for the parameters of the pulse broadening characteristics without simplification assumption w.r.t. the pulse shape and to the order of dispersion. Analysis and simulation shows that it is compatible with the previous theories and more capable of dealing with pulse broadening and distortion in complicated cases, which is the key problem in the high speed optical communication networks. They also found the effect of polarization dependent loss (PDL) in the exploration of polarization mode dispersion.

G. X. Ning, S. Aditya , P Shum, C. Q. Wu, Y. D. Gong and H. Dong [28] provided their ideas toward higher- order polarization mode dispersion: new expressions induced pulse broadening and its compensation. In this paper they derived new expressions for the PMD vector including the second- and third order effects. These new expressions were used to obtain explicit expressions for PMD induced pulse broadening. The pulse broadening expressions reveal that an increase in the first- and second- order derivatives of DGD with respect to frequency always increases pulse broadening. A change of direction of the first order PMD vector also increases pulse broadening. In most cases, the second and third- order PMD cannot be compensated completely. This paper gives the expressions for minimum pulse broadening in the presence of second-and third order PMD. This paper derived the relation between them and the new relation lead to new expression for second and third order PMD induced pulse broadening. They showed that the change of direction of the second- order PMD vector makes the pulse broadening less.

Md Zaini Jamaludin, Ahmad Fauzi Abas, Ahmad Shukri Muhammad Noor and Mohamad Khazani Abdullah in [29] analyzed the first and second order PMD characteristics. They found that a pulse spread of up to 15% of the pulse width is allowed depending on the receiver sensitivity penalty tolerated the system. PMD measurement is also discussed considering Interferometric, Jones- Matrix Eigen analysis (JME) and Fixed Analyzer techniques, from the perspective of field and laboratory applications. They performed the simulation based on realistic parameters of a fiber optic link and the results show that at a 40 Gbps transmission rate, a fiber optic with a PMD coefficient of $0.5\, ps/\sqrt{km}$ can only support up to a 10 km distance.

Sonja Zentner Pilinsky, Zvonimir sipus, and Lubomir Sumichrast described in [30] that Polarization mode dispersion (PMD) occurs in the optical fibers due to circular asymmetries of the fibers core. In the paper, they gave the mathematical description of PMD and some simulations examples of PMD's deleterious impact on high bit-rate transmission systems. PMD can be described locally as fibers birefringence and globally, the birefringence is combined with random polarization mode coupling. They have demonstrated the deleterious effect of PMD on high bit-rates through the simulation. The solution to PMD problem is either to install new, fibers with low PMD, or to try to compensate PMD on already installed fibers.

2.2 Dispersion Mapping

In [31] G.P Aggarwal provides the background material and the mathematical tools needed for understanding the various nonlinear effects. Starting from the Maxwell’s equation, the wave equation in a nonlinear dispersive medium is used to discuss the fiber modes and to obtain the basic propagation equation. The main effect of GVD and dispersion induced broadening is also explained in detail. This book also explains the nonlinear phenomenon of SPM occurring as a result of intensity dependence of the refractive index. Study of higher optical solitons is introduced together with the inverse scattering method used to solve the nonlinear Schrödinger equation. Also focus other nonlinear effects such as XPM, SRS, and SBS. During the description of theory SBS Dr. Aggarwal describes the important features such as the brillouin threshold, pump depletion, and gain saturation.

Fan Zhang, Christian A. Bunge, Klaus Petermann and Andre Richter [32] has presented a numerical study of the performance of 40 Gbps return-to-zero differential phase-shift keying (RZ-DPSK) transmission with different dispersion maps. The optimum dispersion mapping for RZ-DPSK format are discussed and compared with those for on-off keying (OOK). Two pseudo-linear transmission systems, one using standard single-mode fiber and the other nonzero dispersion-shifted fiber, are investigated, respectively. IFWM-induced optical signal-to-noise ratio (OSNR) penalty in RZ-DPSK systems with different dispersion maps by considering nonlinear phase noise – which cannot be studied in terms of OSNR penalty by estimating the bit error rate (BER) via a semi-stochastic method based on the numerical solution of the nonlinear Schrodinger equation.

M. I. Hayee and A. E. Willner in [33] analyzed the 10-Gbps nondispersion-managed and dispersion-managed wavelength-division multiplexed (WDM) systems that use pre-compensation, post-compensation, or dual-compensation of each channel to minimize dispersion and nonlinear effects. A 64-bit pseudorandom nonreturn-to-zero (NRZ) pattern is transmitted at each wavelength. Furthermore, they had described that the optimal amount of pre- or post-compensation depends upon the specific dispersion map used in the WDM system.

In [34] Robert Killey, Hans-Jorg Thiele, Vitaly Mikhailov and Polina Bayvel have reported the results of recirculating fibre loop experiments and computer simulations investigating the use of under-compensation to minimise the nonlinear distortion in multi-span compensated standard-fibre links. By numerical modelling and experiments it is shown that in multispan post-compensated SSMF systems, SPM leads to broadening of short pulses, resulting in vertical closure of the received signal eye after only a few spans. One technique to overcome this effect is the use of under-compensation, as reducing the amount of negative dispersion minimises the broadening of the chirped pulses. In their work they have shown that the under-compensation can be achieved by using a modest amount of positive dispersion at the receiver, a convenient configuration for practical networks, as it can be easily optimised and, by placing it after the demultiplexer, can be tailored for channels individually, to account for differences in channel powers and dispersion slope.

Recently in [35] Xiaoxu Li, Xin Chen, Gilad Goldfarb, Eduardo Mateo, Inwoong Kim, Fatih Yaman and Guifang Li have proposed a universal post-compensation scheme for fiber impairments in wavelength-division multiplexing (WDM) based on coherent detection and digital signal processing (DSP). Transmission of 10 × 10 Gbps binary-phase-shift-keying (BPSK) signals at a channel spacing of 20 GHz over 800 km dispersion shifted fiber (DSF) has been demonstrated numerically. Electrical dispersion compensation (EDC) and electrical nonlinearity compensation (ENLC) are realized simultaneously with coherent detection and DSP.

A. Cauvin, Y. Frignac and S. Bigo [36] show that in single-channel dispersion-managed transmission systems the chromatic dispersion yielding the highest nonlinear impairments depends on the bit rate and the fibre loss according to a practical, dimensionless criterion. In this Letter, the transmission performance at several channel bit rates from 10 to 160 Gbps was computed, while optimising accurately the dispersion management. It is shown that the results can be summarised under a practical dimensionless parameter depending on the bit rate, fibre dispersion, length and loss.

In [37] Chongjin Xie, Inuk Kang, Alan H. Gnauck, Lothar Möller, Linn F. Mollenauer, and Andrew R. Grant have investigated the suppression of intrachannel nonlinear impairments in dispersion-managed (DM) optical fiber transmission systems, using alternate-polarization (APol) on–off keying formats, in which adjacent bits have orthogonal states of polarization. In their work simple methods to generate the APol formats are discussed, and the transmission performance of the APol formats for both 40-Gbps DM systems and 10-Gbps DM-soliton systems is experimentally studied. It is shown that the APol formats can significantly improve the performance of 40-Gbps DM transmission systems, while the improvement of 10-Gbps systems is smaller.

Ruben S. Luís, Daniel Fonseca, António Luís Jesus Teixeira, and Paulo Monteiro in [38] presented an alternative approach to minimize the impact of fiber nonlinearities in optical single-sideband systems at 10 Gbps using electrical dispersion pre-compensation by adding optical post-compensation while maintaining low accumulated dispersion. Numerical simulation had been used to show that the dependence of the system performance on the dispersion compensation scheme resembles a pseudo linear transmission regime, although it is not considered as such in the strictest sense. A launched power increase of 3 dB is achieved when compared to full electrically pre-compensated systems. A feasible implementation of the optical transmitter is considered, which imposes a maximum transmitted modulation depth. It is reported by them that low modulation depths result in an asymmetric optimum dispersion compensation map.

Chapter-3 Effects of PMD over Optical Communication System

In this chapter, the effects of the Polarization Mode Dispersion (PMD) over the optical communication system are studied. The PMD is varied from 0 to 140 $ps/\sqrt{km}$, and the impact is studied on the parameters like eye opening, eye closing output optical spectrum. The fiber used is considered as lossless and idle to the chromatic dispersion and other nonlinear effects so that all the variation in the results is due to the PMD. It is reported that the PMD is having adverse effect on the eye opening, eye closing, and power at the output. It is reported that up to the PMD value of 20 $ps/\sqrt{km}$, the value of eye opening and output power is decreased, and beyond this value, fluctuations in the above parameters are observed.

3.1 Introduction

Polarization Mode Dispersion, or PMD for short, is an important *linear* phenomenon occurring inside optical fibers that affects the performance of modern fiber-optic communication systems adversely. For a given fiber, PMD is supposed to be fixed. However, this is not the case in real communication systems because environment fluctuations cause PMD to vary randomly in time, which makes it difficult to compensate for PMD. Therefore, it is important to understand the statistical properties of pulse propagation induced by PMD.

While the phenomenon of Polarization Mode Dispersion (PMD) has been known for years, it has only been recently that it has posed a serious, realistic problem for optical networks. PMD's negative effects result in a limitation of a networks bandwidth or length that is, of course, undesirable to say the least.

As laser light is generally highly polarized, the digital bits that they emit contain light that is also highly polarized. Couple this with the birefringence present in the fiber and the result is that different components (polarizations) of the digital bits travel at different velocities [39]. In other words some of the light in the bit travels faster and some of the light travels slower. This causes the digital bit to spread in time; this is termed dispersion. Moreover, the residual birefringence is not constant along the length of the fiber but changes with distance in a random way, not only in amount, but also in its local principal axes. For a given fiber, PMD is supposed to be fixed. However, this is not the case in real systems because environment fluctuations cause PMD to vary randomly in time. Therefore, it is important to understand the statistical properties of pulse propagation induced by PMD.

3.2 Simulation Setup for PMD Variation

The figure (3.1) shows the structure for the analysis of PMD variation in optical link. The PMD is varied in eight steps from 0 to 140 $ps/\sqrt{km}$. The transmitter and receiver section are connected by the dispersive fiber link. The transmitter section consists of data source (Datasource), modulator driver (Dtriver_NRZ_raised_cosine), laser source (Lorentzian_laser, 1550) and modulator (Modulator_sin2). Data source produces a pseudo-random sequence of bits at a rate of 2.5 Gbps. The output of data source is given to modulator driver which produces a NRZ (Non return to zero) format pulse train. The transmitted signal is formed by modulating the light carrier by the NRZ data source. The light carrier is generated by Lorentzian laser source at the 1550 nm wavelength. The properties of modulator driver and laser source are tabulated in the table (3.1 and 3.2).

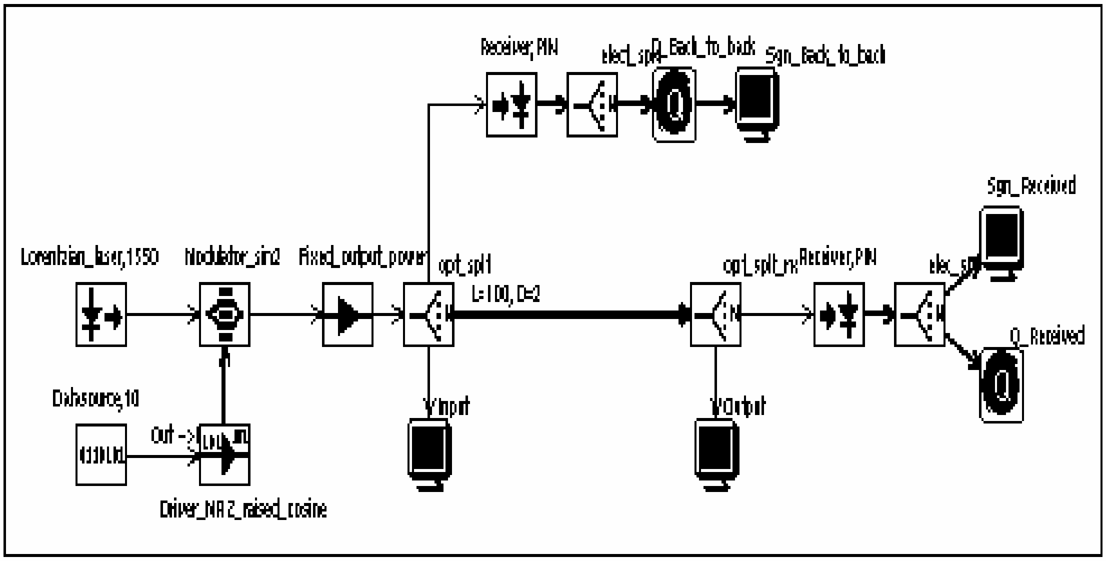

Figure 3.1: Simulation Setup for PMD variation effects.

The transmitter output is boosted up by the fixed gain Erbium Doped Fiber Amplifier (fixed_output_power). There are two types of optical amplifiers; Semiconductor Optical Amplifier (SOA) and the Erbium Doped Fiber Amplifiers (EDFA). Due to its high gain characteristics EDFA are used these days. The shape of the gain graph is flat having a gain of 25 dB. The noise figure value is set at 4.5 dB. The transmission medium used is a standard single mode fiber (L=100, D=2) of 100 km length. The properties of standard single mode are shown in table 3.3.The receiver used is the system is the PIN (Receiver, PIN) receiver, which uses the PIN (p-intrinsic-n) diode as a detector. The pin photodiode simulated had 70% quantum efficiency. The dark current was simulated at 0.1 nA. The output of the receiver is given to the measurement devices which are fed through the electrical splitter (elec_splt), the electrical scope (Sgn_Received) and the Q estimator (Q_Received). The optical spectrum of the signal is observed from optical spectrum analyzer (input and output) by splitting the signal from fiber link with the use of optical splitters (opt_splt and opt_splt_rx). To analyze the effects due the variation of PMD on the specified parameters, the PMD is taken as global parameter.

Parameter	Value
Low Level	0.0
High Level	5.0

Duty cycle	0.5

Table 3.1: Properties of Modulator driver

Parameter	Value
Center emission wavelength(nm)	1550
Center emission frequency(GHz)	193.41
CW power(mw)	0.0
CW power(dB)	1.0

Table 3.2: Properties of Laser

S. No.	Parameter	SSMF
1.	Core Effective Area (m^2)	80×10^{-12}
2.	Loss @ λ = 1550 nm (dB)	0.0
3.	Non linearity reference wavelength (nm)	1550
4.	Zero dispersion wavelength (nm)	1391.5
5.	Nonlinearity refractive index	2.5×10^{-20}
6.	β_2 (ps^2/km)	-20.407
7.	β_3 (ps^3/km)	0.14745
8.	Fiber Birefringence	on
9.	Fiber PMD (ps/$km^{0.5}$)	0.1

Table 3.3: Properties of Standard Single Mode Fiber (SSMF)

Parameter	Value
Excess loss(dB)	3.0
% Transmission per applied voltage	20.0
Chirp factor	0.0

Table 3.4: Properties of Amplitude Modulator

3.3 Results and Discussions

The figures shown below are the results obtained for the different values of Polarization Mode dispersion. The PMD is varied from 0 to 140 $ps/\sqrt{km}$ in four steps. After the simulation run, the results showing the impacts of the PMD variation on the system performance are discussed below. The results are obtained in the form of eye diagrams, optical spectrum and standard deviation. The values of eye opening, eye closing and power evaluation are plotted against the specified values of PMD. After taking a look on the results it can be easily observed that beyond the value 20 $ps/\sqrt{km}$, PMD causes the fluctuation in the output signal.

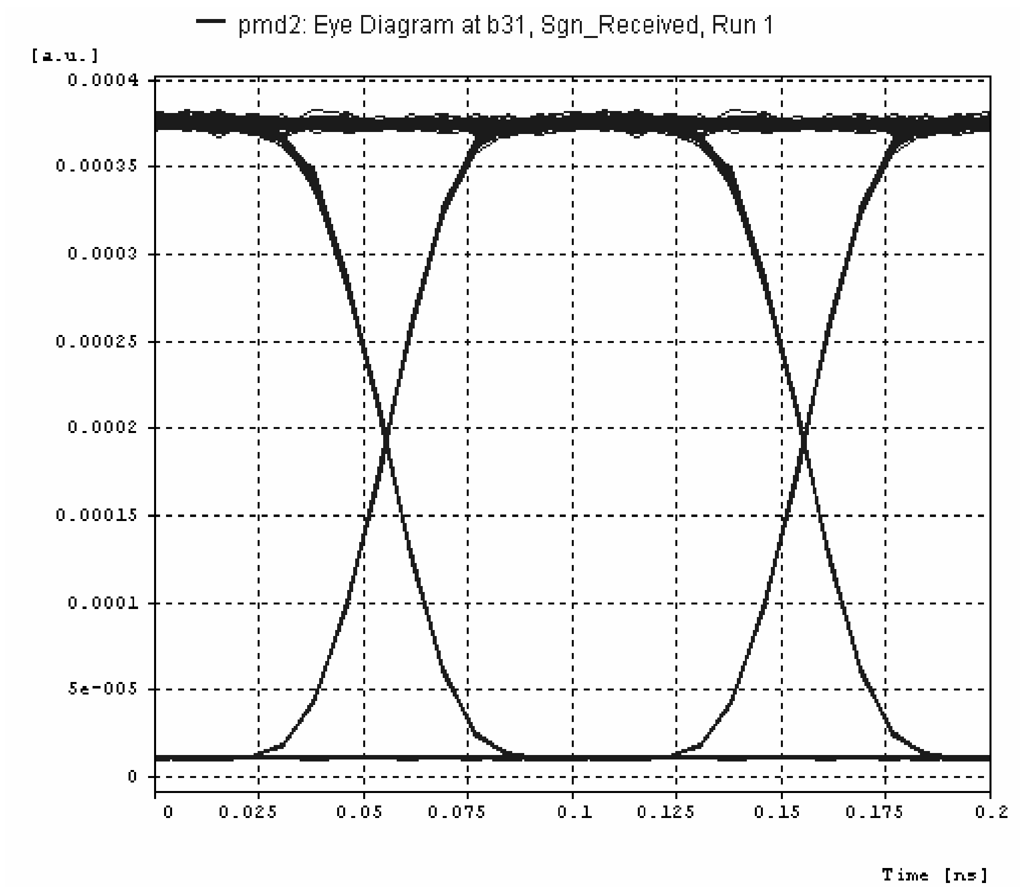

Figure 3.2: Eye Diagram at PMD= 0 $ps/\sqrt{km}$

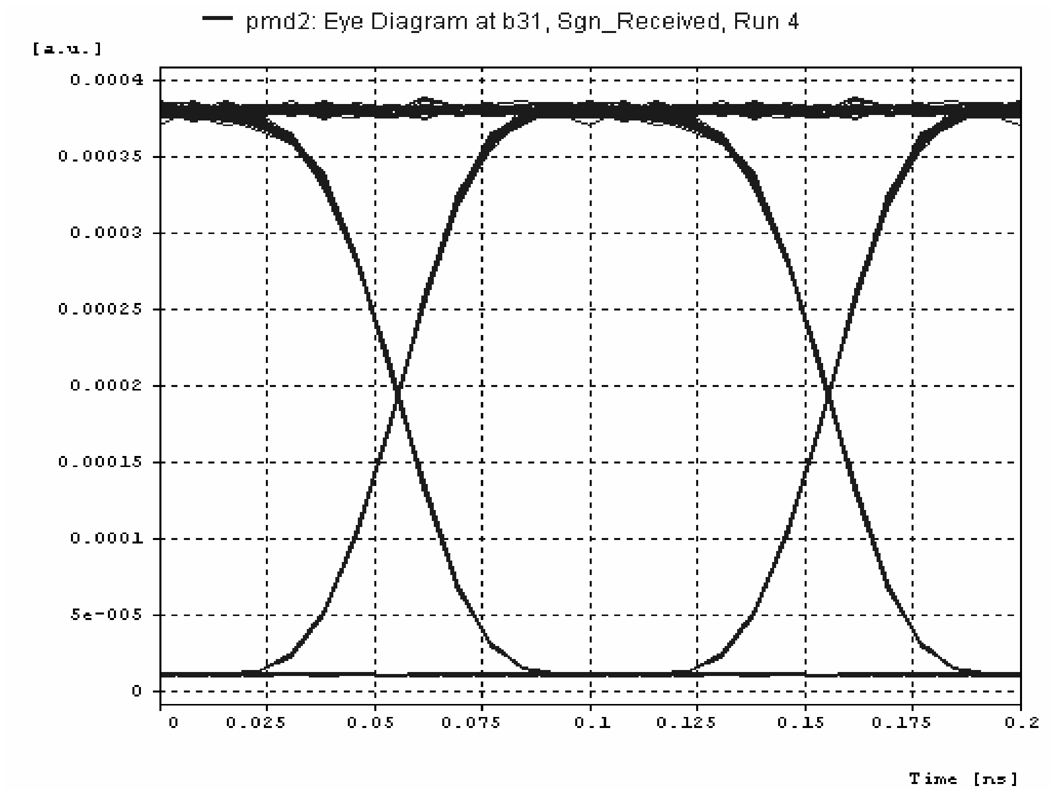

Figure 3.3: Eye Diagram at PMD= 60 $ps/\sqrt{km}$

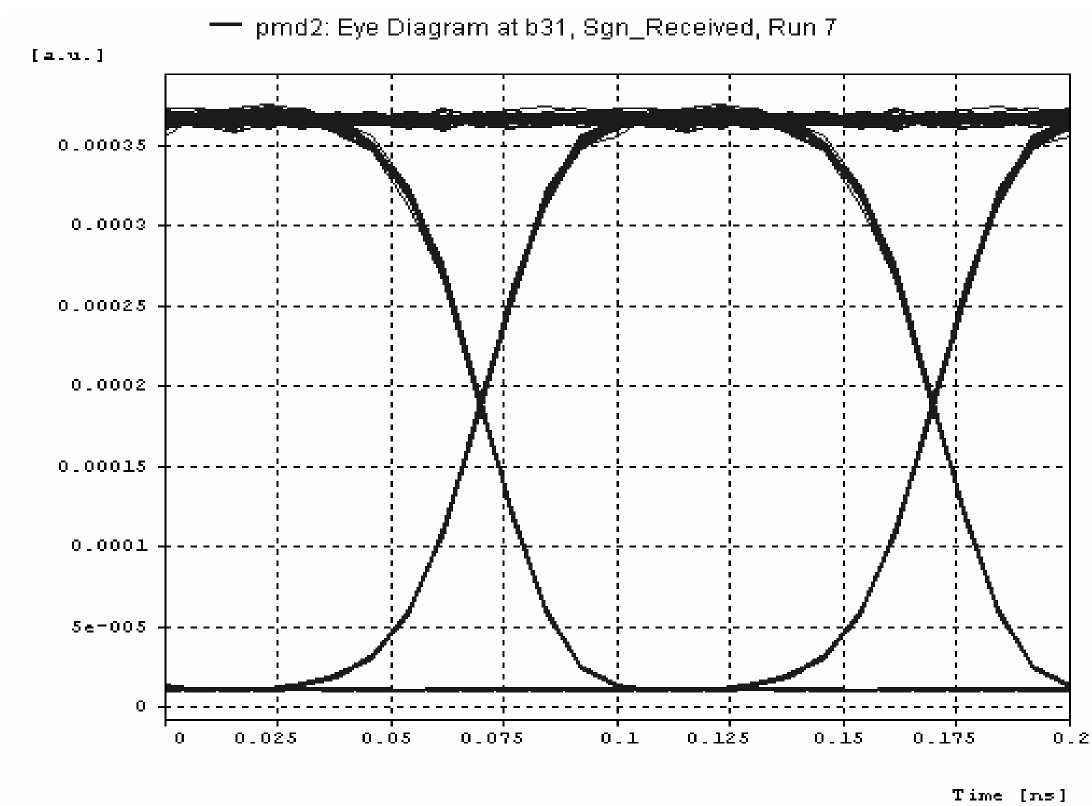

Figure 3.4: Eye Diagram at PMD= 120 $ps/\sqrt{km}$

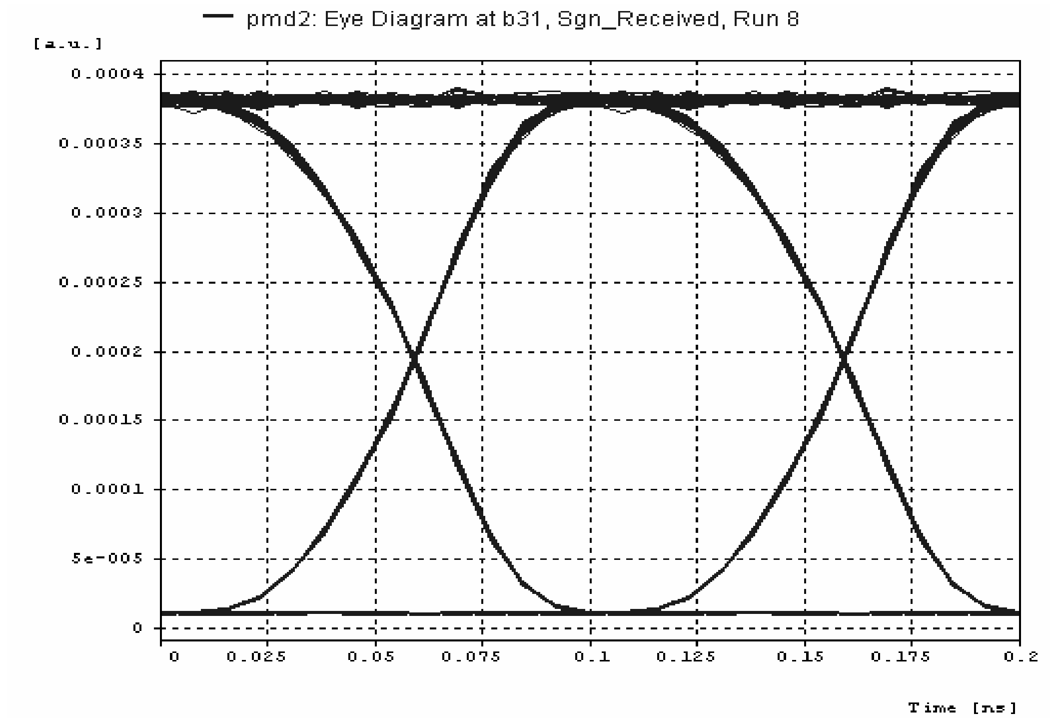

Figure 3.5: Eye Diagram at PMD= 140 $ps/\sqrt{km}$

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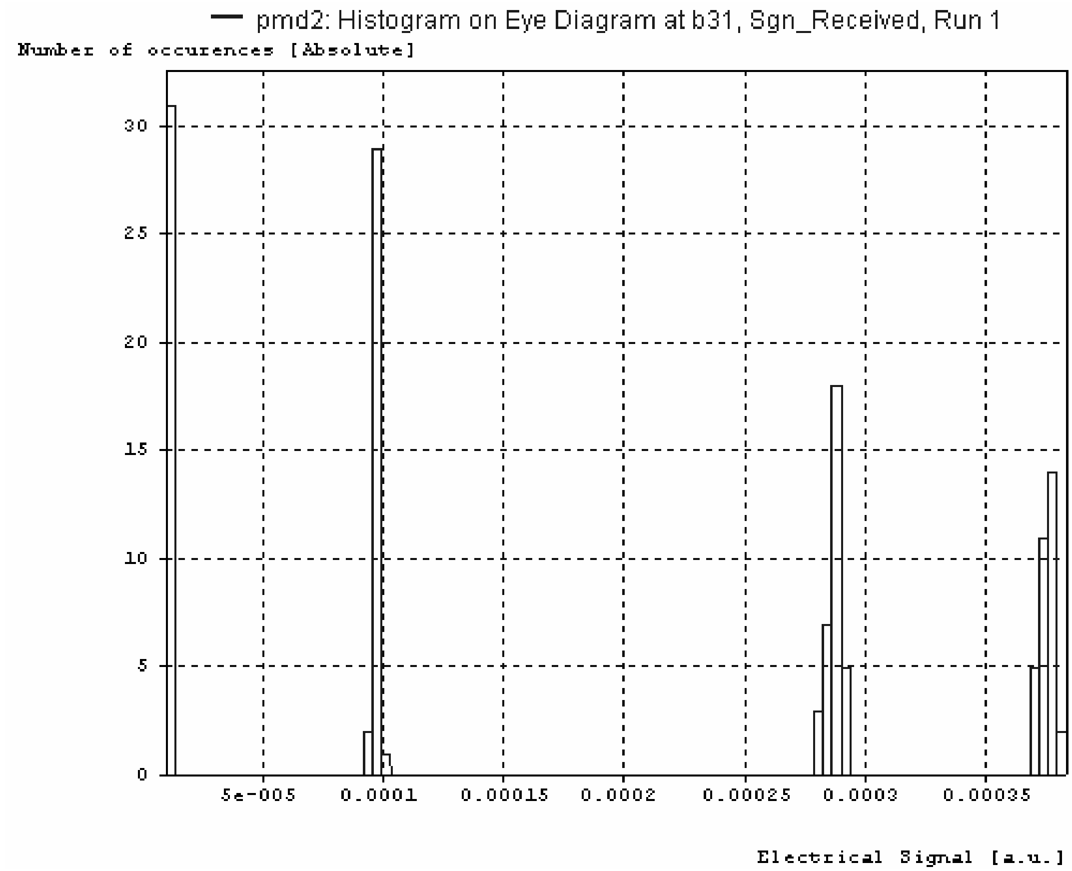


Figure 3.6: Eye Histogram at PMD=0 $ps/\sqrt{km}$

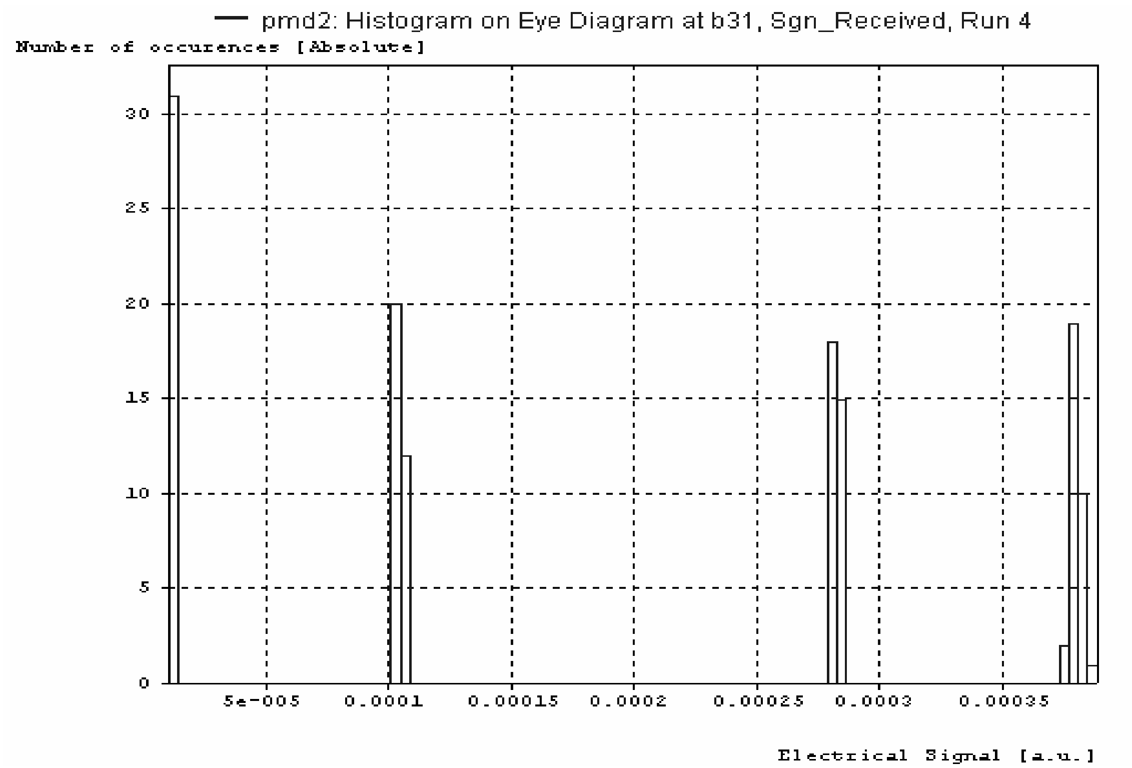


Figure 3.7: Eye Histogram at PMD=60 $ps/\sqrt{km}$

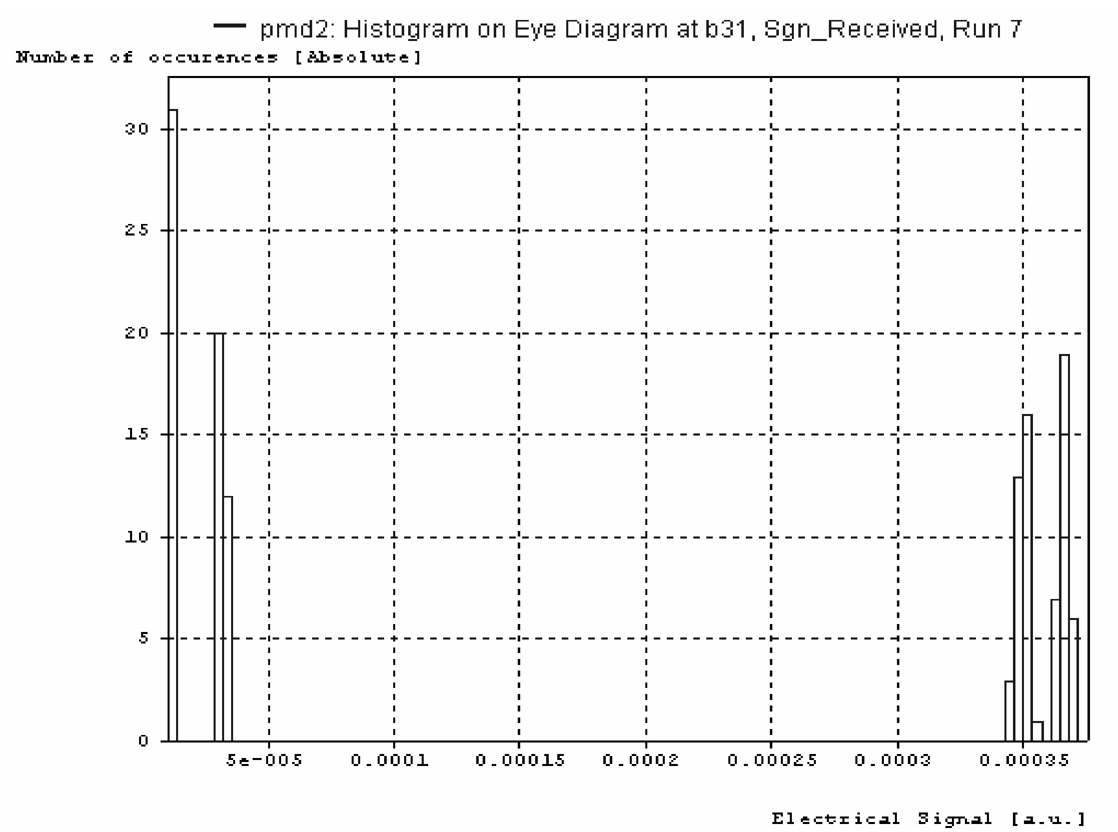


Figure 3.8: Eye Histogram at PMD=100 $ps/\sqrt{km}$

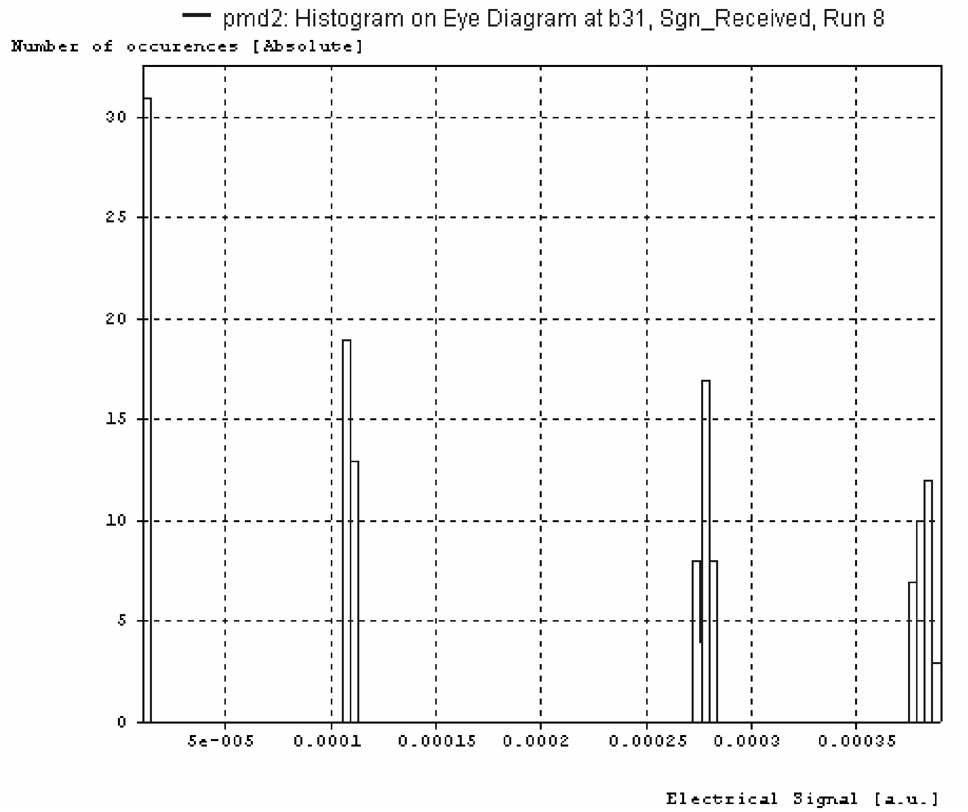


Figure 3.9: Eye Histogram at PMD=140 $ps/\sqrt{km}$

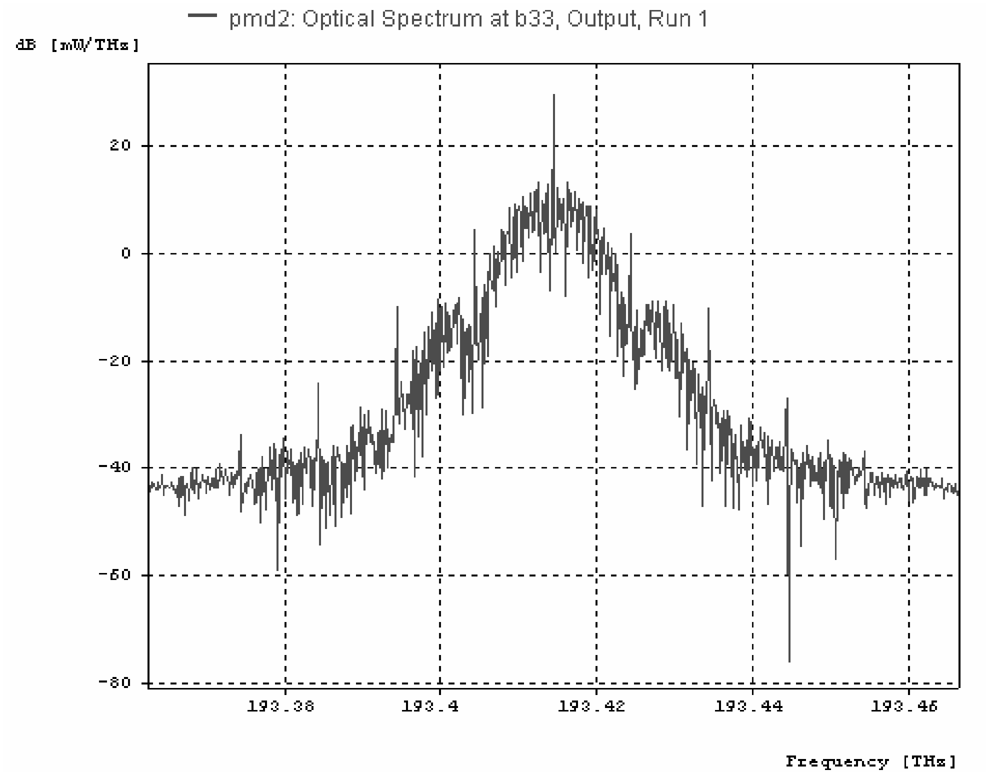


Figure 3.10: Optical Spectrum at PMD=0 $ps/\sqrt{km}$

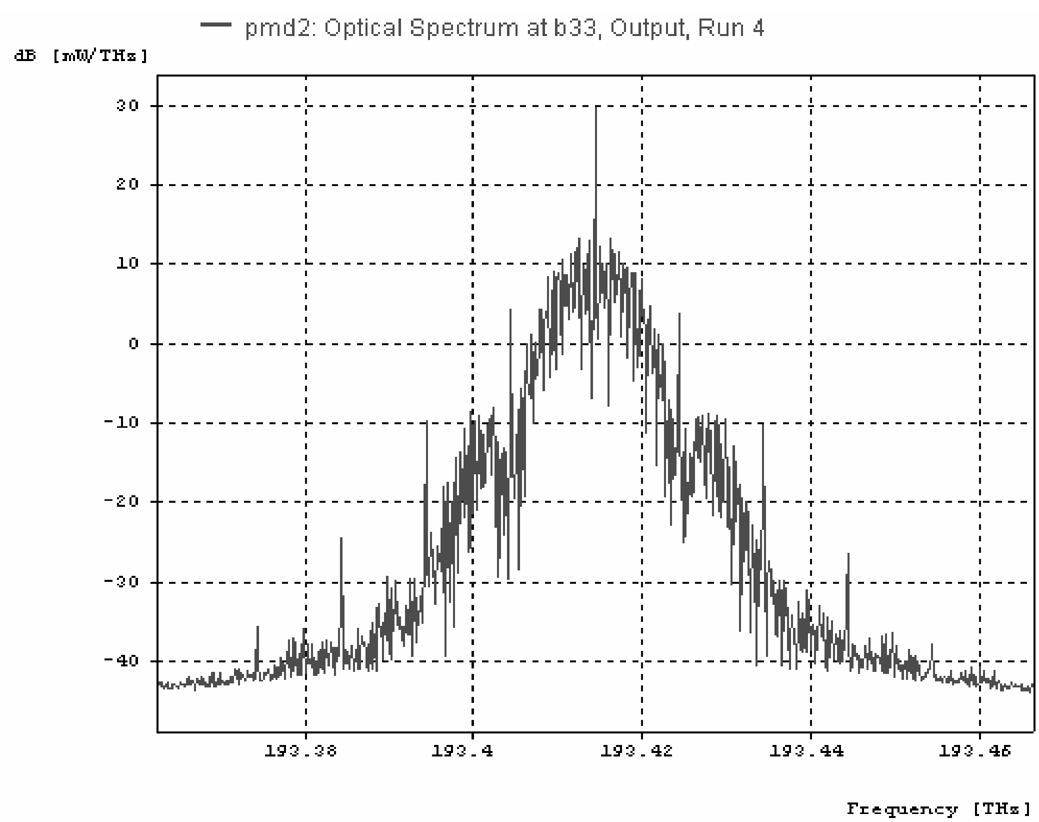


Figure 3.11: Optical Spectrum at PMD=60 $ps/\sqrt{km}$

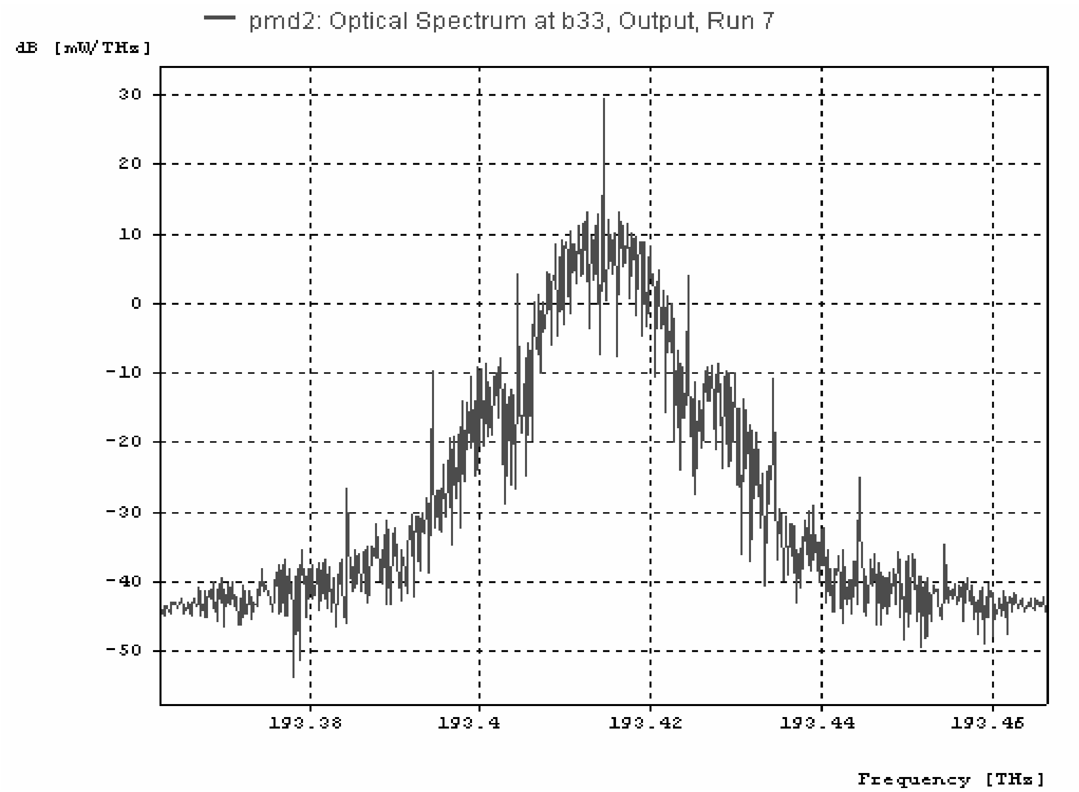


Figure 3.12: Optical Spectrum at PMD=100 $ps/\sqrt{km}$

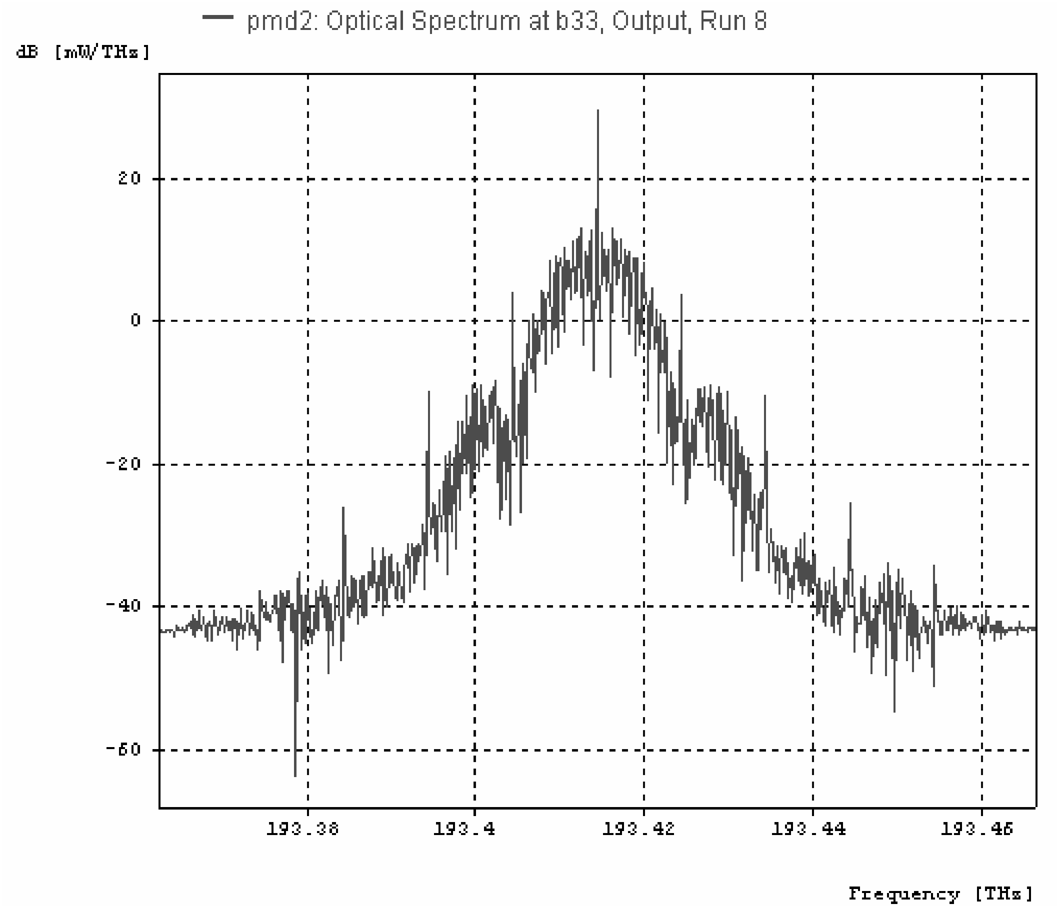


Figure 3.13: Optical Spectrum at PMD=140 $ps/\sqrt{km}$

As clear from the above figures that the PMD is having adverse effect on the eye opening, standard deviation, power at the output. The figures (3.2 to 3.5) show the impact of PMD on the eye diagram. It is observed that with the increase in PMD coefficient the eye is closing. This means that the performance of the system is getting weakened as the PMD increases. Further the figures (3.6 to 3.9) are the histograms on the eye diagram at the corresponding values of PMD. The figures from (3.10 to 3.13) show the optical spectrum of the optical signal travelling through the dispersive optical link. In the above simulation Q-factor is used to be 40dB and the Bit Error Rate (BER) is $1\text{x}10^{40}$. As the value of PMD increases, the above factors increases and after PMD reaches 60 the above factors start decreasing, then after PMD reaches 100 the above factors start increasing again.

In further figures the values of the earlier described parameters i.e. eye opening, eye closing and power evaluation are plotted. The plots show that PMD effects do not follow a particular trend.

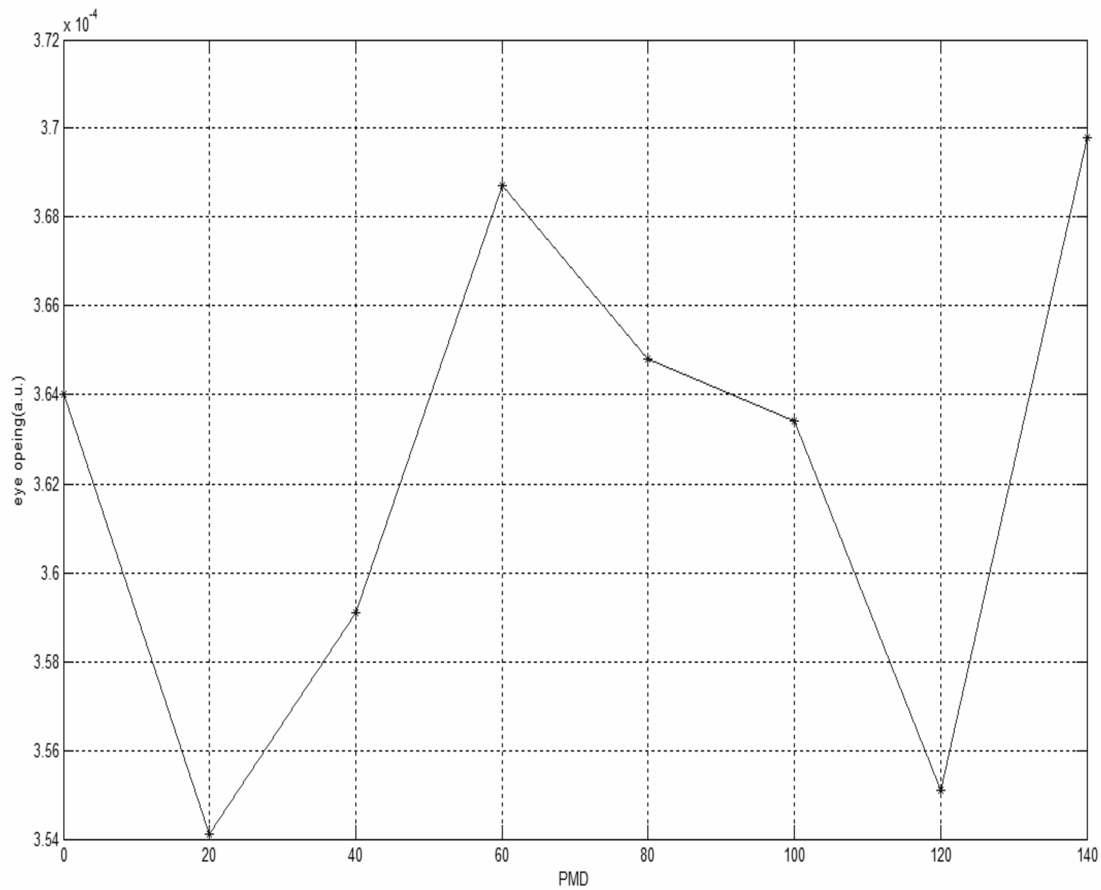


Figure 3.14: Eye Opening at Different values of PMD

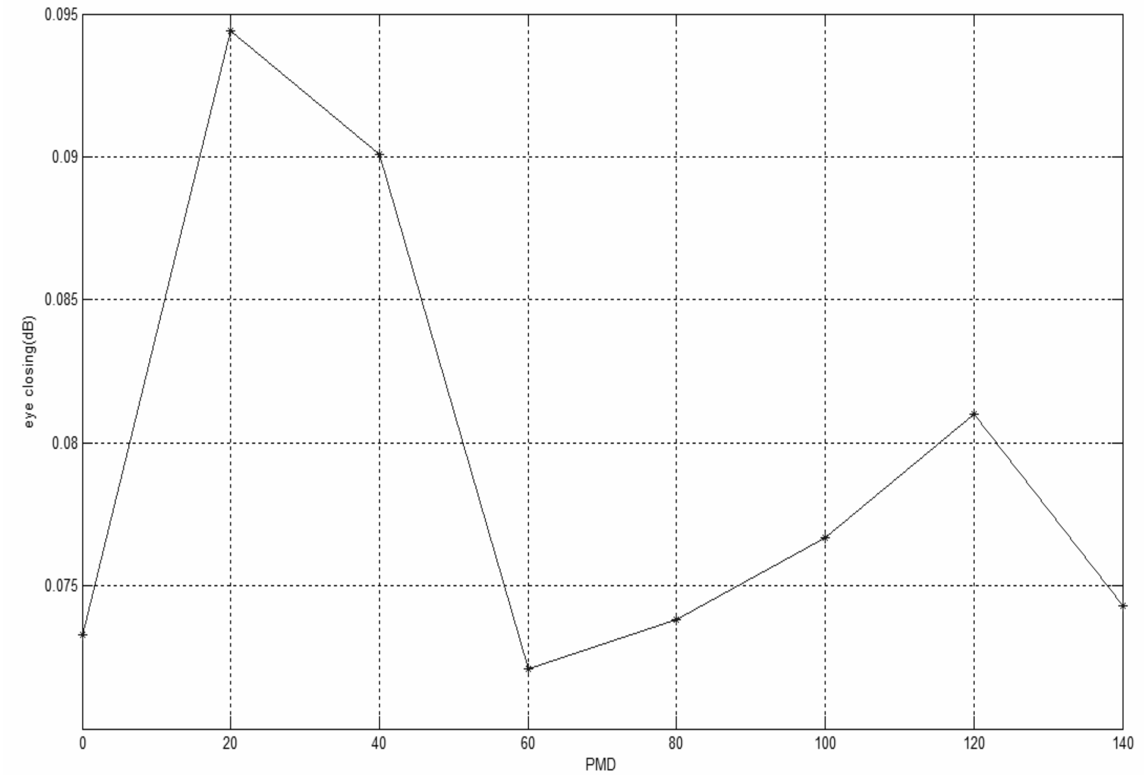


Figure 3.15: Eye Closing at Different values of PMD

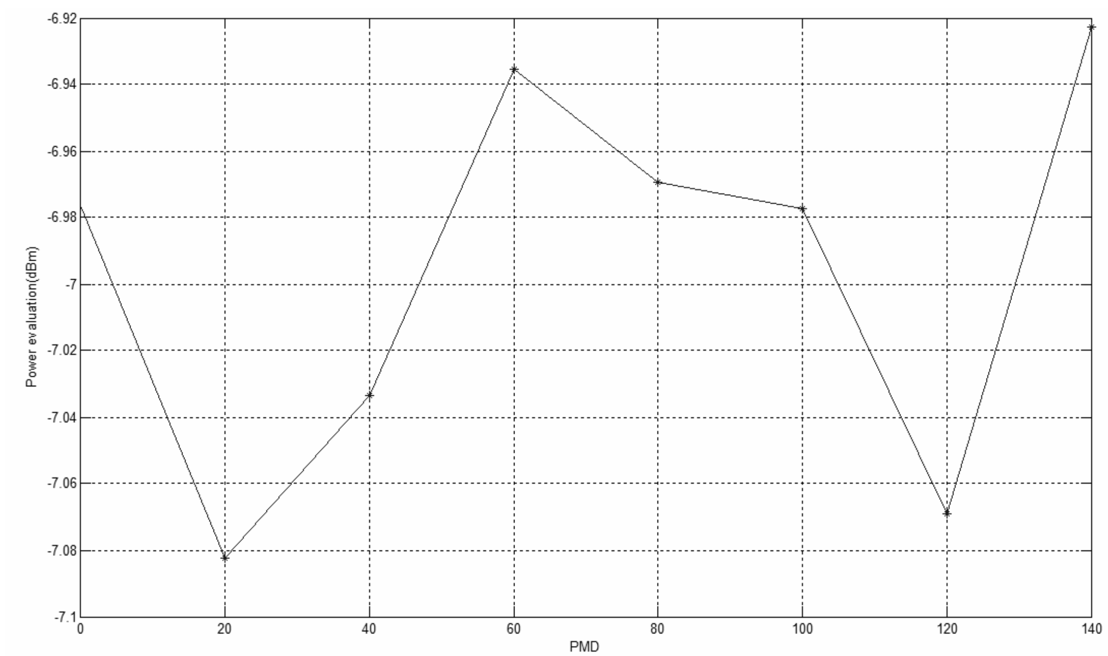


Figure 3.16: Power Evaluation at Different values of PMD

The figures (3.14 to 3.16) describe the variation of the important parameters due to the variation in PMD. Figure (3.14) shows the variation of eye opening value, figure (3.15) of the eye closing and the figure (3.16) give the variation plot of power evaluation due to the PMD. It is observed that eye opening increases as PMD increases from 20 to 60 $ps/\sqrt{km}$. After the PMD value of 60 $ps/\sqrt{km}$, the eye opening decreases up to minimum value at 120 $ps/\sqrt{km}$. The adverse impact of PMD variation over power is also observed in figure (3.16). At 0 PMD power is -6.98 dBm and it is reduced to -7.09 dBm 20 $ps/\sqrt{km}$. But an abrupt rise is seen as PMD goes to 60 $ps/\sqrt{km}$ to the power -6.96 dBm. After that again a slow reduction of power is found for 120 $ps/\sqrt{km}$.

3.4 Conclusion

The effect of changing the value of PMD is reported in this chapter. This effect is seen from the eye opening, eye closing and output power characteristics. The above discussed results show that the behaviour of PMD becomes unpredictable at higher values of PMD. It is reported that up to the PMD value of 20 $ps/\sqrt{km}$, the value of eye opening and output power decreased. It is studied that any further increase in value of PMD causes the great fluctuations in the characteristics of the measured parameters.

Chapter-4 High Speed Transmission Limitations due to PMD

In this chapter, the impacts of Polarization Mode Dispersion on the performance of Optical communication system are studied. Three simple Optical communication systems are studied with different bit rates. The two systems are built using older fibers with same Polarization Mode Dispersion (PMD) coefficient at different bit rates and third is built with new fiber with less PMD coefficient than that of the previous two. Attenuation, Chromatic dispersion and Non linear effects have been disabled, so that all the variation of the results is due to PMD. The bit rate is varied from 2.5 Gbps to 40 Gbps and the length is varied from 1000 km to 20,000 km. The output is observed at receiver end on the scope. It is shown that the impact of PMD increases with the bit rate of system. It is also observed that the impact of PMD becomes intolerable at the bit rate of more than 40 Gbps. Also the PMD produces very minute impact on the system performance for same bit rate with the variation in the fiber length.

4.1 Introduction

The polarization related impairments have become a major obstacle to the increase of transmission rates in WDM systems. If the amount of dispersion is excessive, adjacent light pulses will overlap and interfere with each other. This interference will manifest itself as an increased Bit Error Rate as the receiver may be unable to discern adjacent bits from each other. Polarization Mode Dispersion is one of the critical problem for high bit rate transmission systems.

The single mode fibers manufactured in mid 1990s have the property that has become more problematic as the bit rates and span lengths increases. This all was due to the imperfectly rounded fiber core. So as it is impossible to manufacture the perfectly symmetrical and rounded fiber, the researchers got success to produce more symmetrically rounded fiber. But the problem of PMD still exists with a small coefficient of 0.1 $ps/\sqrt{km}$ [7].

The researchers had the fear that as the optical communication system is getting faster and sending signals at longer distances, the major physics related problem the PMD will become the hurdle. The technology had given a free ride as it grew up from 90 Mbps to 270 Mbps to 435 Mbps to 2.5 Gbps. Now if we switch over to 10 Gbps form 2.5 Gbps, in the 10 Gbps system, the time interval between each pulse or bit is reduced by a factor of 4 since 10 Gbps is four times faster than 2.5 Gbps. So as the bit rate is increased from 2.5 Gbps to 10 Gbps the pulses got closer to each other. When the PMD comes into effect the closer pulses got broadened and overlapped. So as the bit rate increases the impact of the PMD increases, which cause more distortion in the signal. So this problem was not discovered until the early 1990s. It can distort signals, render bits inaccurate, and destroy the integrity of a network.

This chapter is divided into four sections. In section 2 the simulation setup for PMD variation effects in optical communication system is discussed with component details. The performance of the system at various PMD coefficients is analyzed. The Section 3 gives the simulation setup to study the bit rate limitations imposed by PMD. The section 4 gives the discussion of the results observed after the simulations. And the section 5 gives the conclusion of the dependence of the system performance at different bit rates.

4.2 Simulation Setup

The system architecture shown in figure (4.1) is build to study the impacts of Polarization Mode Dispersion over the different bit rates. In the setup three simple optical transmission systems are compared with each other on the basis of fiber PMD coefficient and bit rates. The older and new fibers with PMD coefficient 2 $ps/\sqrt{km}$ and 0.1 $ps/\sqrt{km}$ respectively are used in this simulation setup. The first two transmitter sections transmit at different bit rates of 2.5 Gbps and 10 Gbps and the bit rate of the third transmitter is varied from 2.5 Gbps to 40 Gbps. In the third transmission system the fiber length is also varied to find impact of PMD with variation in fiber length at the same bit rate.

In the transmission section the signal generator generate the digital information in the electric form at the specified bit rate. The transmitters use the external NRZ modulation to modulate the optical carrier signal from the laser source with the electrical signal from the signal generator. In this setup two transmitters are generating signal at 2.5 Gbps and 10 Gbps while the third transmitter is kept with the ability to transmit at from 2.5 Gbps to 40 Gbps.

The output of the transmitter section is directly fed to the fiber section. Attenuation, Chromatic dispersion and Non linear effects have been disabled, so that all the distortion of the waveforms is due to PMD. The PMD coefficient of the older fibers is set at 2 $ps/\sqrt{km}$ and for new fiber it is set at 0.1 $ps/\sqrt{km}$.

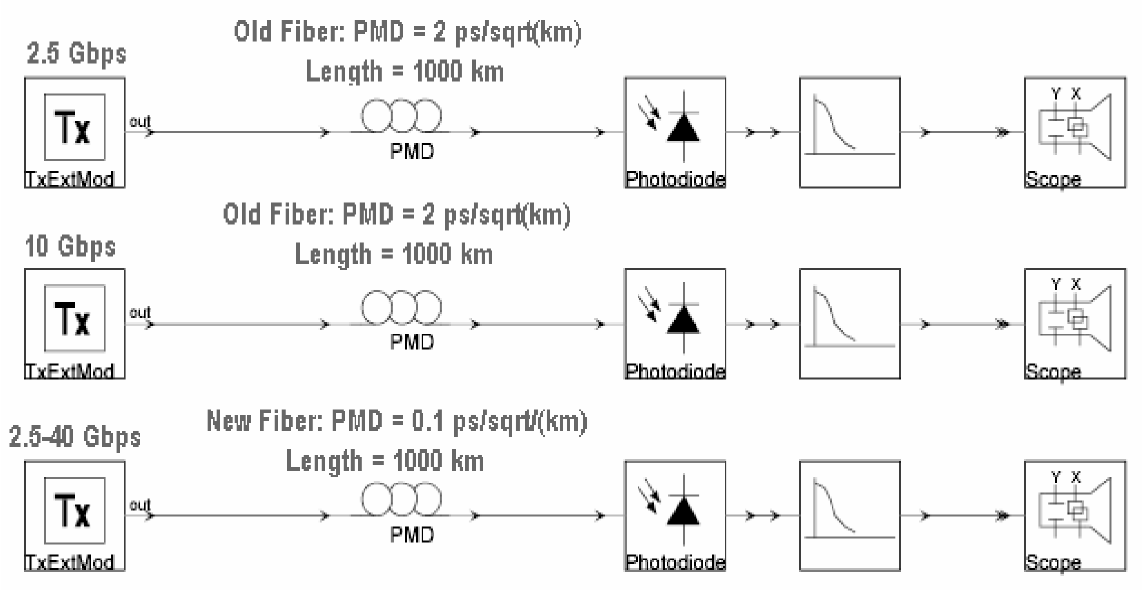


Figure 4.1: Simulation Setup for PMD impact over different Bit Rates.

The fiber is connected to the photo detector which is simple a photo diode. The electrical output of the photo detector is observed through the signal analyzer. The analyzer is used to drive the x-y scope which generates the eye diagram according to the system performance for the bit rate of the input signal.

To see impact of the PMD over bit rate the outputs of the three systems are compared at different bit rates. The bit rates of the first two systems, containing the older fibers with PMD coefficient 2 $ps/\sqrt{km}$ is fixed at the 2.5 Gbps and 10 Gbps. The bit rate and the length of the new fiber in the third system is kept variable with limits from 2.5 Gbps to 40 Gbps. Bit rate of the third system is varied in five discrete steps with values of 2.5, 5, 10, 20 and 40 Gbps. The results are observed for each bit rate at x-y scope in the form of eye diagram.

At the end, to find the PMD impact with the fiber length variation; the length of the new fiber in the third system is varied from 1000 km to 20,000 km. Results are again obtained in the form of eye diagram at the system end.

4.3 Results and Discussions

In this chapter the impacts of Polarization Mode Dispersion over the speed of optical network transmission have been reported. The simulation setup was demonstrated with different optical systems at different bit rates. Also the results with the varied transmission length are shown with same bit rates. As discussed in previous sections that PMD produces its effects over the system performance, the results showing the performance are discussed below with different transmission speed and length.

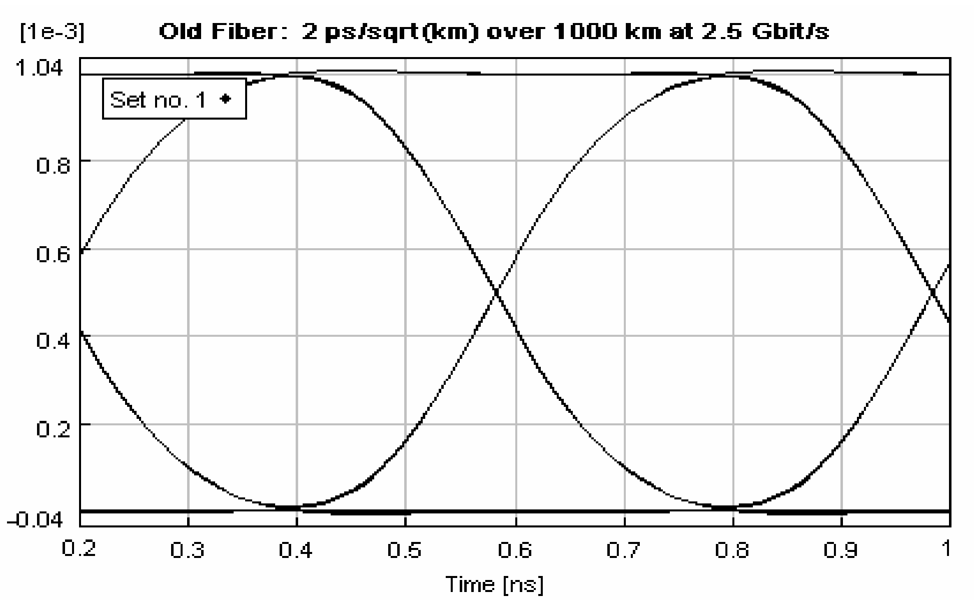


Figure 4.2: Eye Diagram of system performance at 2.5 Gbps with PMD 2 $ps/\sqrt{km}$

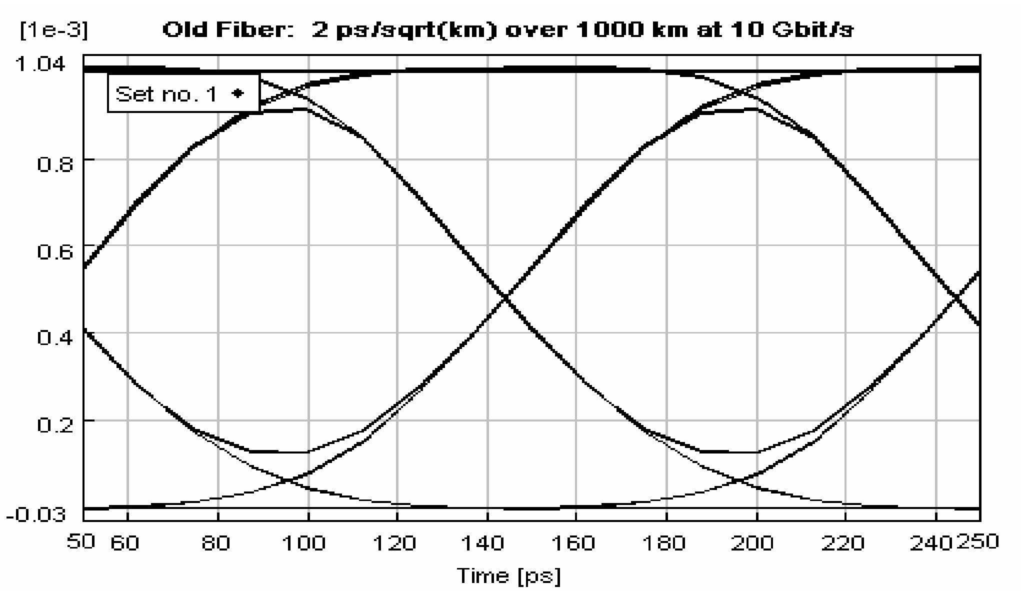


Figure 4.3: Eye Diagram of system performance at 10 Gbps with PMD 2 $ps/\sqrt{km}$

The figure (4.2 and 4.3) shows the eye diagram of the output of the systems at transmission rates of 2.5 Gbps and 10 Gbps respectively with fiber of PMD coefficient of

2 $ps/\sqrt{km}$. In the figure 4.2 the eye is very clearly open and in good shape. The closing eye in the figure 4.3 describes the greater impact of PMD over 10 Gbps transmission rate.

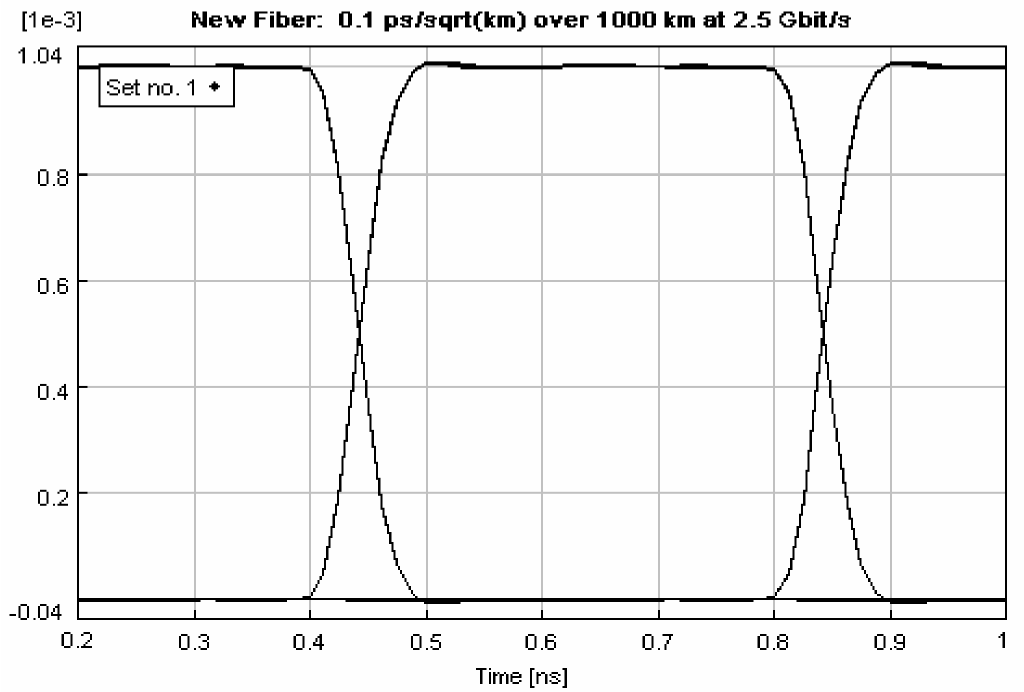


Figure 4.4: Eye Diagram of system performance at 2.5 Gbps with PMD 0.1 $ps/\sqrt{km}$

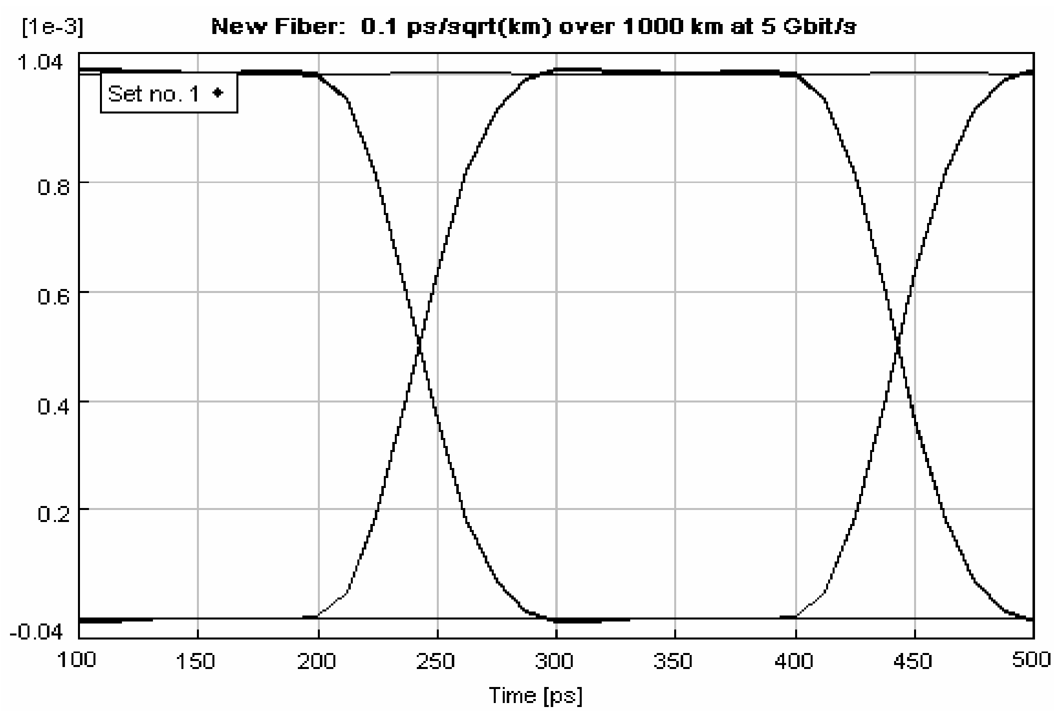


Figure 4.5: Eye Diagram of system performance at 5 Gbps with PMD 0.1 $ps/\sqrt{km}$

The figure (4.4 and 4.5) shows the eye diagrams of the systems with PMD 0.1 $ps/\sqrt{km}$ at the transmission rate 2.5 Gbps and 5 Gbps respectively. It can be easily observed from above two figures that the PMD impact increases as the bit rate of the system increases.

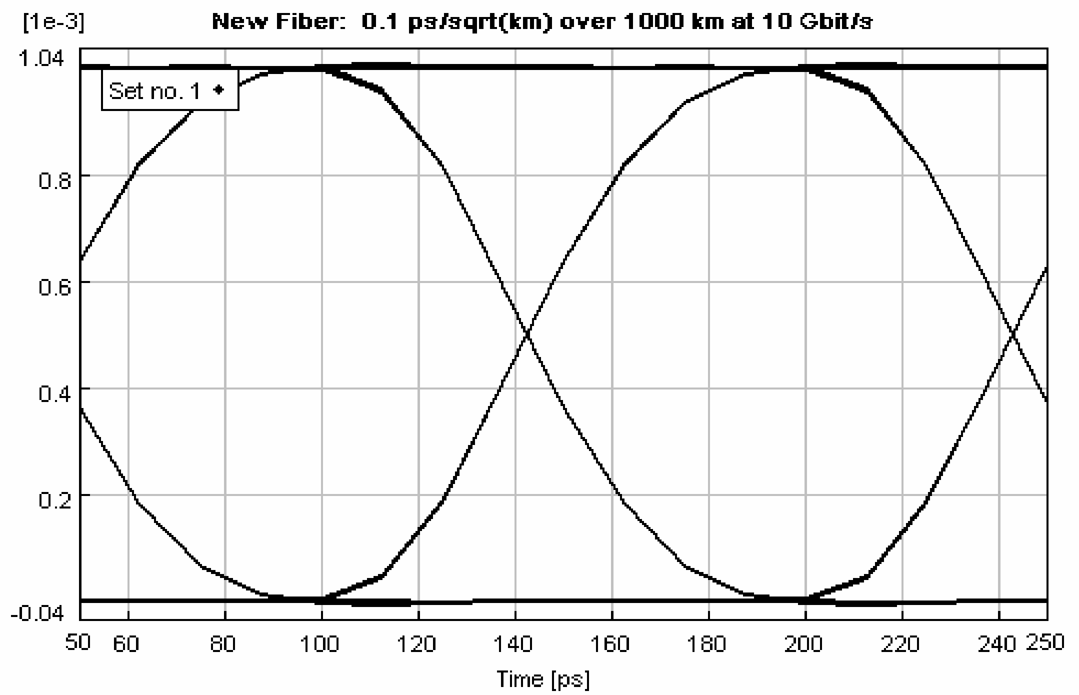


Figure 4.6: Eye Diagram of system performance at 10 Gbps with PMD 0.1 $ps/\sqrt{km}$

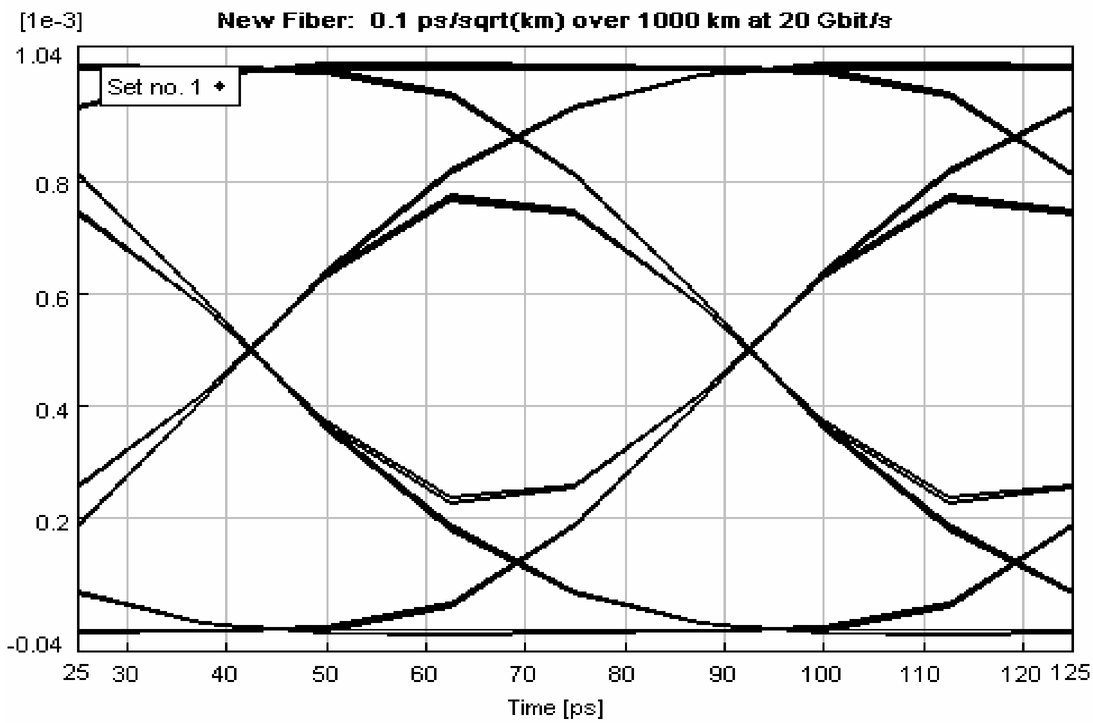
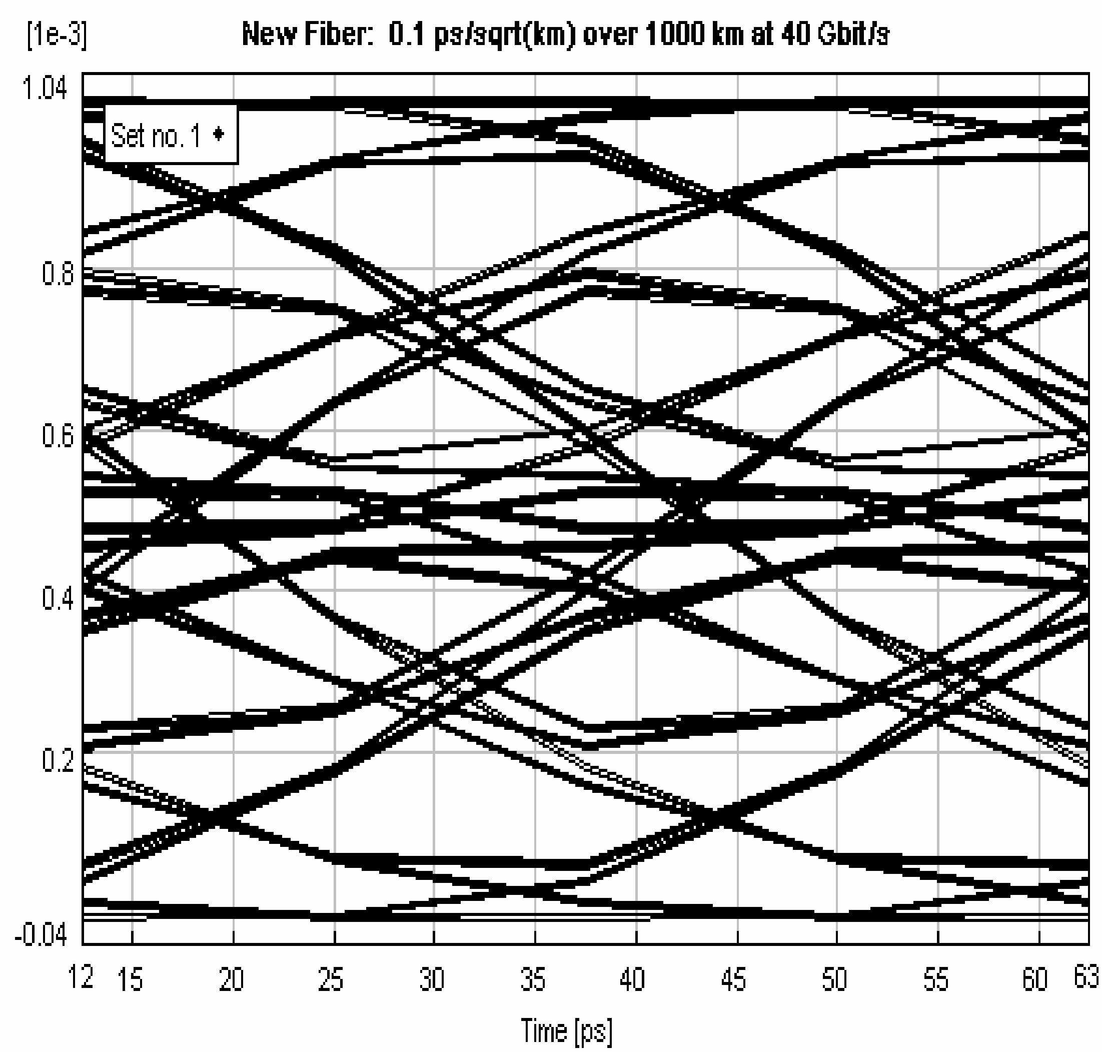


Figure 4.7: Eye Diagram of system performance at 20 Gbps with PMD 0.1 $ps/\sqrt{km}$

The figures (4.6 and 4.7) give the output eye at 10 Gbps and 20 Gbps respectively. The above figures confirm the increasing impact of PMD with increase of transmission rate of the system. The eye is closing more and more with the increase of rate of the data transmission.



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igure 4.8: Eye Diagram of system performance at 40 Gbps with PMD 0.1 $ps/\sqrt{km}$

The figure (4.8) shows the intolerable impact of the PMD at the bit rate of 40 Gbps. The eye is completely closed, which describe that signal is completely distorted. It makes clear that the Polarization Mode Dispersion puts the limitation over the system at the rate of 40 Gbps.

The further results describe the impact of PMD with increase in the fiber length. The figures (4.9 to 4.13) show the eye diagrams for the link length of 20,000 km with different bit rates. From the figures below it is observed that impact of PMD also increases with the fiber length. If eye diagrams at 20,000 km compared with there same bit rate companions at length of 1000 km, it will be found that the eye closure is very small due to PMD at that much greater length (20,000 km) of fiber which is 20 times greater than that of the previous link at the same bit rate. This shows that there is very small degradation in the system with increase in the link length at same bit rate.

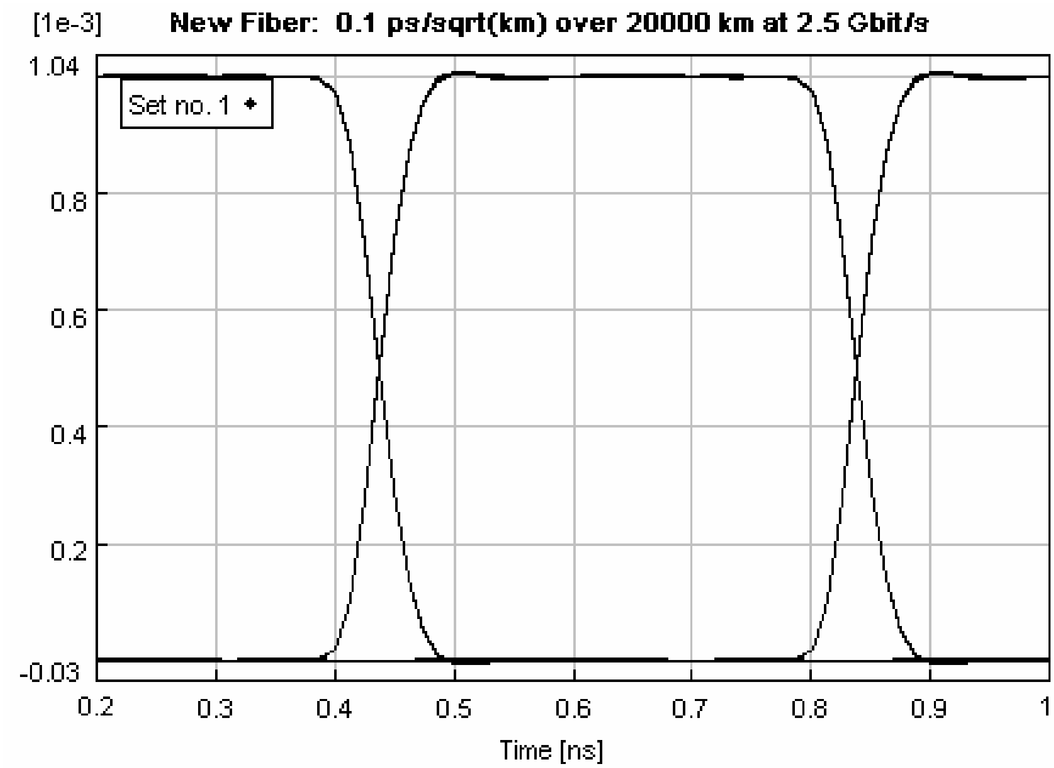

Figure 4.9: Eye Diagram of system performance at 2.5 Gbps Fiber Length 20000 km

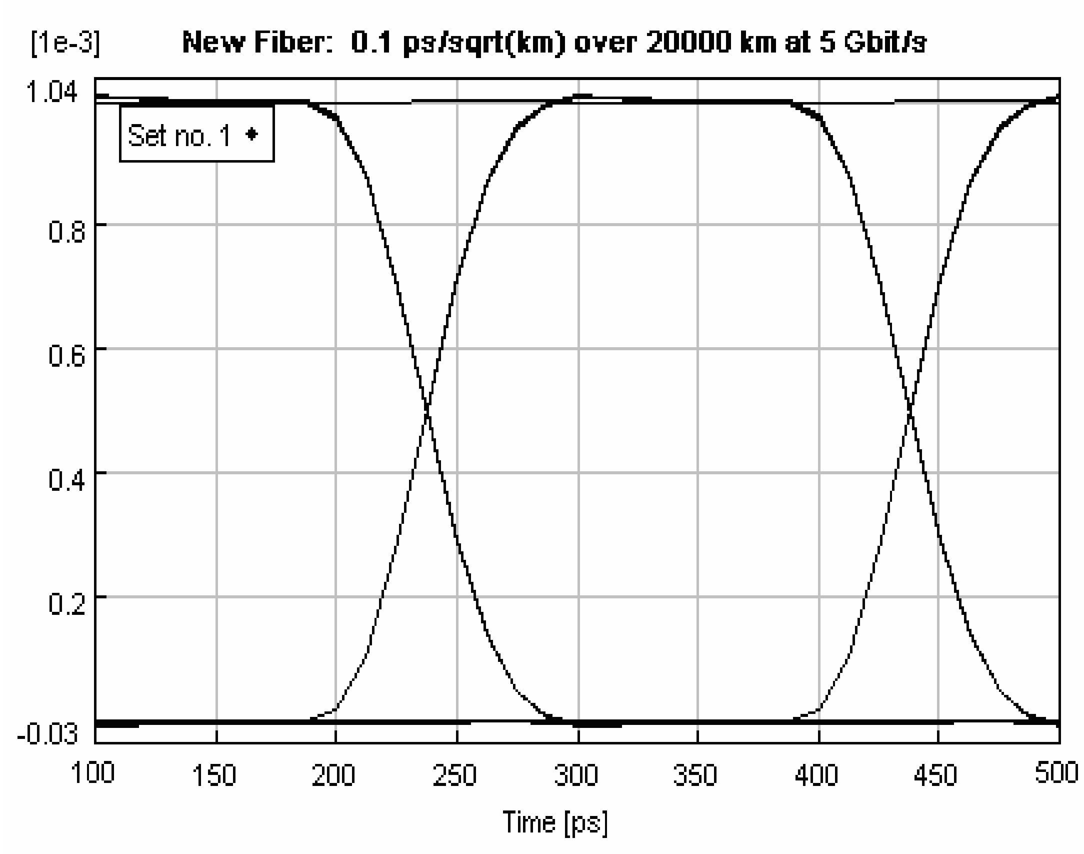

Figure 4.10: Eye Diagram of system performance at 5 Gbps with Fiber Length 20000 km

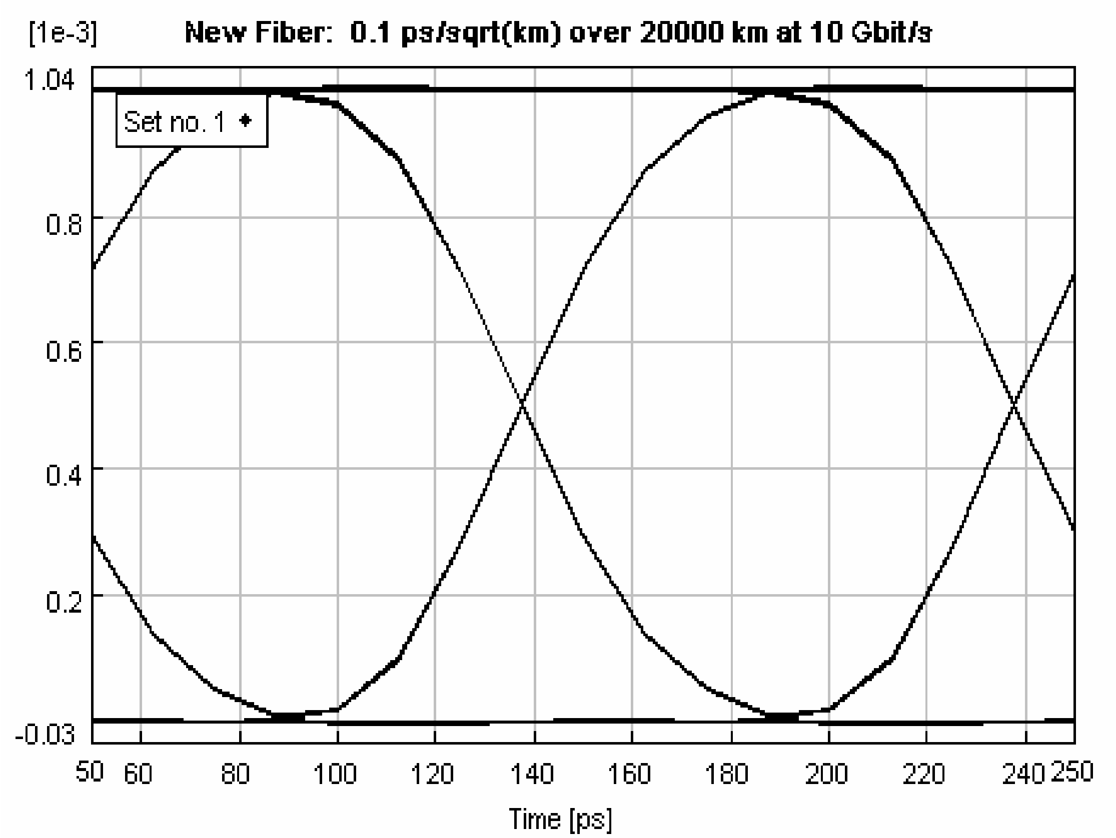

Figure 4.11: Eye Diagram of system performance at 10 Gbps with Fiber Length 20000 km

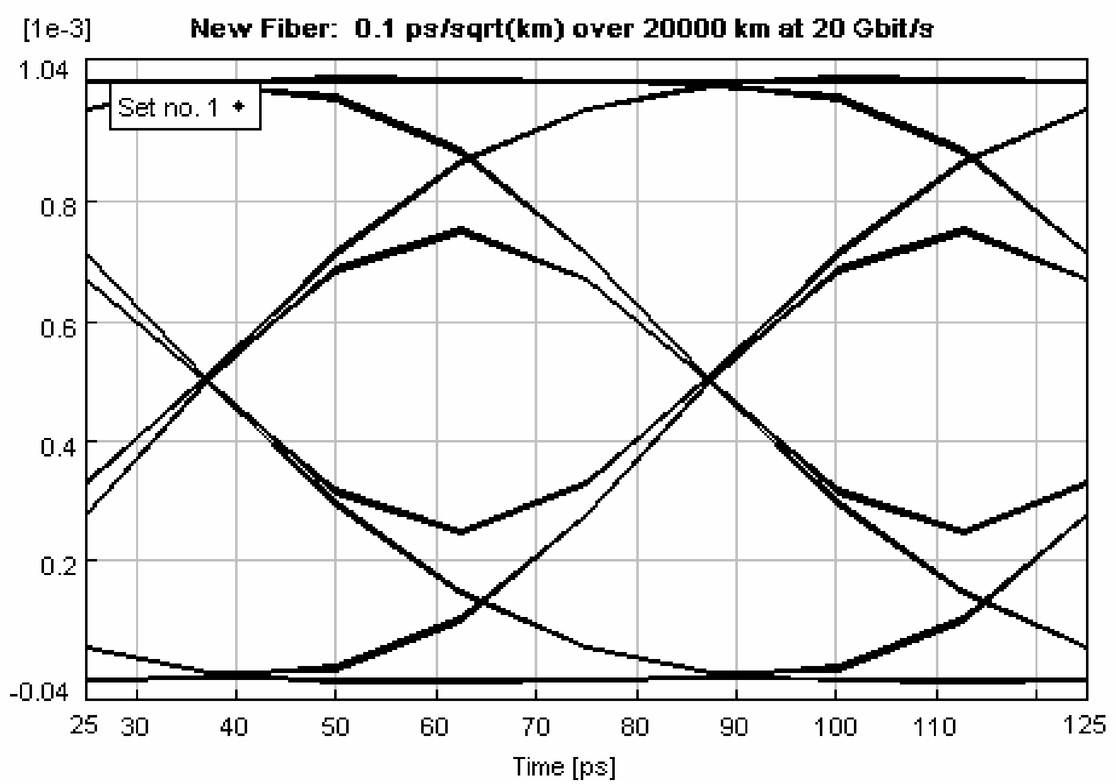

Figure 4.12: Eye Diagram of system performance at 20 Gbps with Fiber Length 20000 km

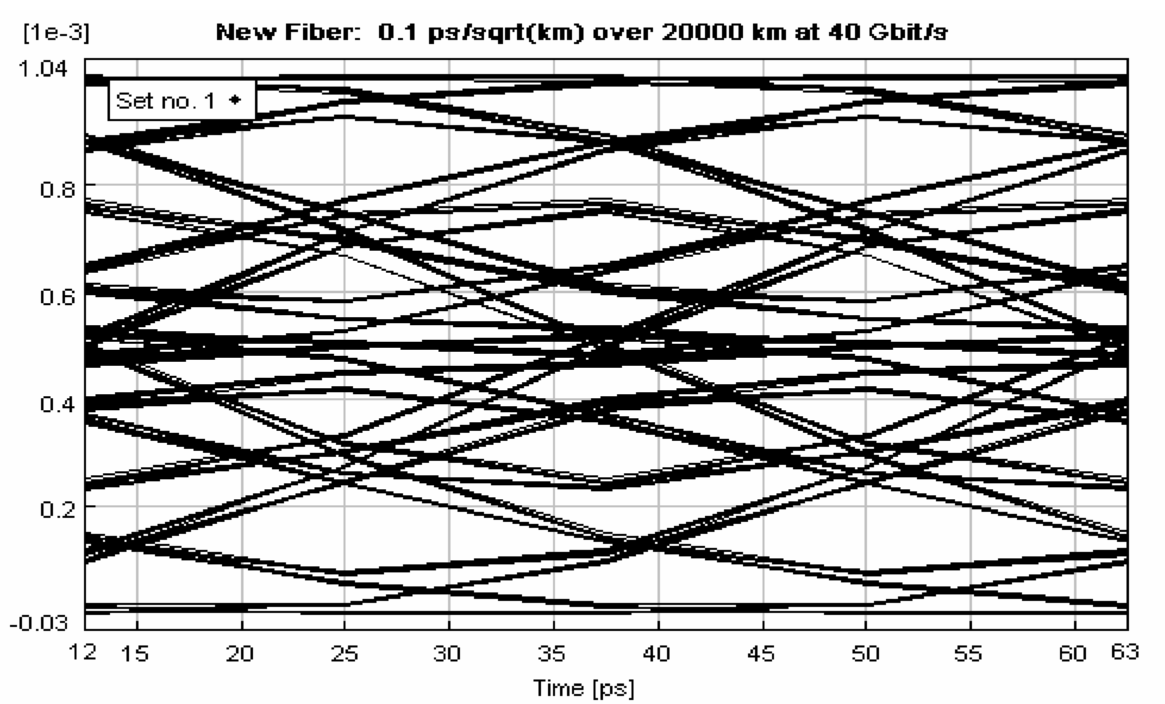

Figure 4.13: Eye Diagram of system performance at 40 Gbps with Fiber Length 20000 km

So as described by the results shown through the figure (4.9 to 4.13), there is also performance degradation of the transmission system with increase in the fiber length. But this effect is negligible as compared to the effect produced by the increase in bit rate.

4.4 Conclusions

Form the above results in the form of eye diagrams; it is observed that Polarization Mode Dispersion puts more impact over the system as the bit rate increases. The older fibers having the PMD coefficient of 2 $ps/\sqrt{km}$ shows the performance degradation with increase in bit rate. But as the new fibers have reduced PMD coefficient up to 0.1 $ps/\sqrt{km}$ also puts impact to degrade the signal quality of the communication system. At 10 Gbps PMD is no more negligible however at higher bit-rates of 40 Gbps and above, it represents the major limitation in optical transmission systems. So if we have to move further to the higher bit rates, the PMD mitigation is necessary. The results also show that PMD effects also increase with the increase in fiber length. But this effect is negligible as compared to the effect due to the increase in the bit rate.

Chapter-5 Comparison of Dispersion Mapping Techniques

In this chapter, the dispersion maps in the presence of fiber Nonlinearity in 10 Gbps and 40 Gbps CSRZ (Carrier Suppressed Return to Zero) systems are compared. Three channels using different compensation methods are fed by the same RZ transmitter. Each consists of 80 km of Standard Single Mode Fiber and pre, post, and hybrid-compensation modules. The fiber line is considered as noise less in order to compute the impact of non linear impairments. The dispersion compensation is pre-compensated, post-compensated or symmetrically or Hybrid-compensation. The input power is varied to see the non linear effects. The Bit error rate with each compensation method with and without non linear effect is plotted against the input power.

5.1 Introduction

In high-capacity wavelength division multiplexed (WDM) transmission systems, the increase of the channel bit rate from 10 Gbps to 40 Gbps and above changes the nature of the dominant nonlinear impairments. As transmission distance and number of channels increases, signals become more vulnerable to a number of debilitating fiber nonlinear effect. To combat this, network operators routinely ensure that signal power levels remain below a “safe” threshold, where the degradation induced by the nonlinearities is negligible. A key point here is that the knowledge of the general nonlinear characteristics of a link is not enough information to fully characterize these effects of nonlinearities on a systems, due to the following reasons:(i) chromatic dispersion variation with temperature changes the nonlinearities effects and (ii) periodic repair and maintenance of the fiber plant can alter the properties of the link itself, both resulting in changes the power penalty. Important work on the computation of non linear penalties for various bit rates is done in [40]. The key nonlinear effects in such systems are self phase modulation, cross phase modulation and four wave mixing. SPM is an intra channel effect and is present even in single channel systems while XPM and FWM are present only in multi channel systems. These effects can be dynamic and will change as the power and wavelength makeup the channels changes.

Fiber nonlinearity compensation was first proposed in 1996 using materials with a negative nonlinear coefficient [41], which are impractical. After that the [42, 43] virtually used that idea with the help of electronic dispersion compensation. Electronic Dispersion Compensation (EDC) [44] is of growing interest because it self adapts to any fiber system, including dynamically-switched optical networks, so reduces engineering and inventory costs. *Arthur James Lowery* has used the EDC in [45] for long haul optical links using OFDM. Also in [46, 47] the work on the electrical pre-compensation of RZ signal at 10 Gbps and on Symmetric compensation respectively.

In this chapter the dispersion maps in the presence of fiber Non Linearity in 10 Gbps and 40 Gbps RZ (Return to Zero) systems are compared. Also the effect of nonlinearities on the variation of input power is analyzed. This chapter is divided in four sections. In section 2 the simulation setup for the comparison of three dispersion maps in presence of fiber nonlinearities at high bit rates is discussed with component details. The performance of the system at 10Gbps and 40Gbps with pre compensation, post-compensation and hybrid-compensation is compared. Section 3 gives the discussion of the results observed after the simulation. And the section 4 gives the conclusion of the dependence of the system performance with three dispersion maps.

5.2 Simulation Setup

To investigate the performance of the three different dispersion mapping techniques at 10 Gbps and 40 Gbps with nonlinearity impairments, the structure used is shown in figure (5.1). Three fiber links are provided with the pre, post and hybrid-compensation are modelled.

As shown in figure (5.1), at the transmitter there is data source that produces a CS-RZ sequence at rate of 10 Gbps and 40 Gbps. The RZ modulation format is used because these pulses occupy just a part of the bit slot, resulting in a duty cycle value smaller than 1. In particular the carrier suppressed RZ modulation is used for high bit rates. The main target of this modulation format is the reduction of nonlinear impacts in a transmission line and an improvement of the spectral efficiency in high bit rate WDM systems. Additionally, it can be expected that the dispersion tolerance of the transmission can be improved as well by CS-RZ modulation, due to its reduced spectral width compared to conventional RZ modulation. Optical noise is also considered in the transmitter section. The output of the transmitter is given to the fork which splits the signal into three fiber links which are provided with the three different dispersion mapping systems.

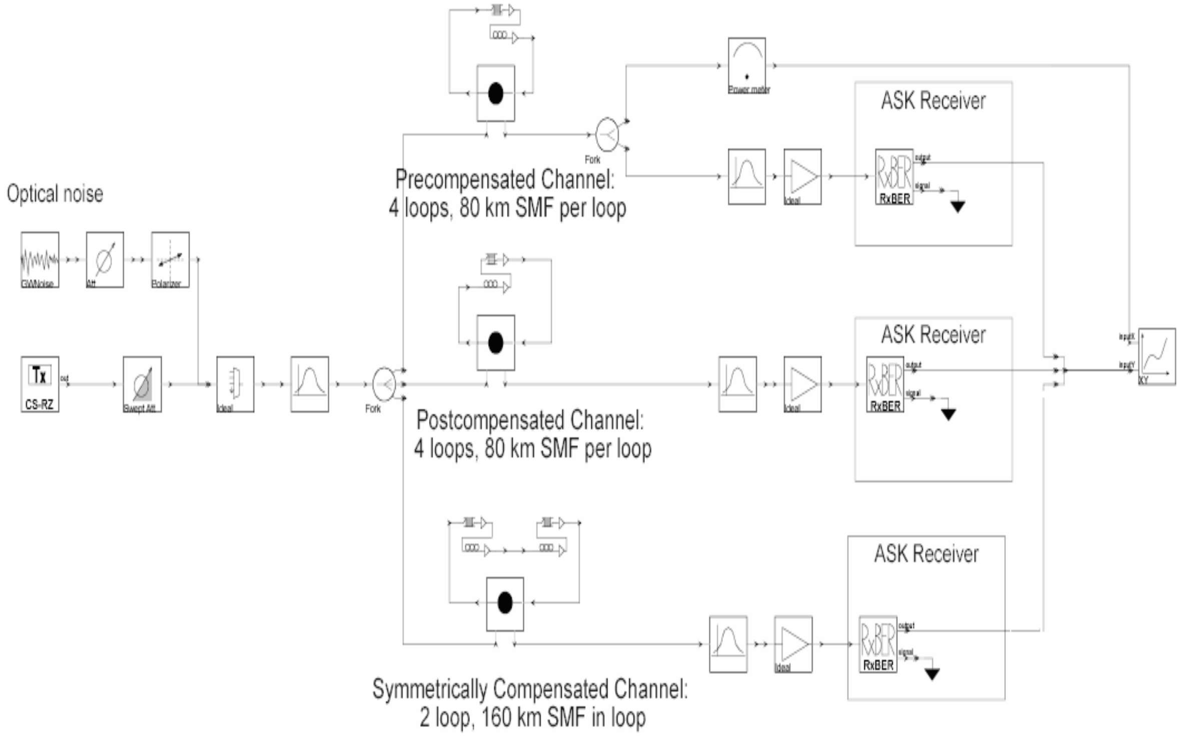

Figure 5.1: Simulation Setup for Dispersion Maps at 10 Gbps & 40 Gbps.

The links are provided with the dispersion maps i.e. pre-compensation, post-compensation and symmetric or hybrid compensation. The output of each link is obtained at the ASK receivers. The output of the receivers is combined and fed to the x-y plotter at y-axis port. The other port of the x-y plotter is fed through power meter, which observe the power of the optical signal and convert the same into the electrical form so as to take plot of BER with three compensation techniques w.r.t input power. The figures given below are the screen shots of zoomed setup of dispersion compensation techniques.

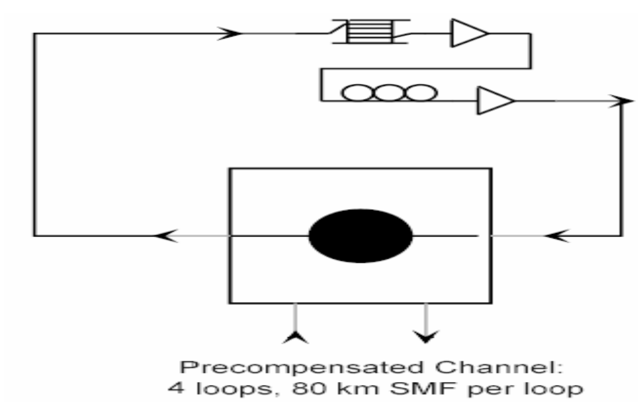

Figure 5.2: Pre-compensation channel setup.

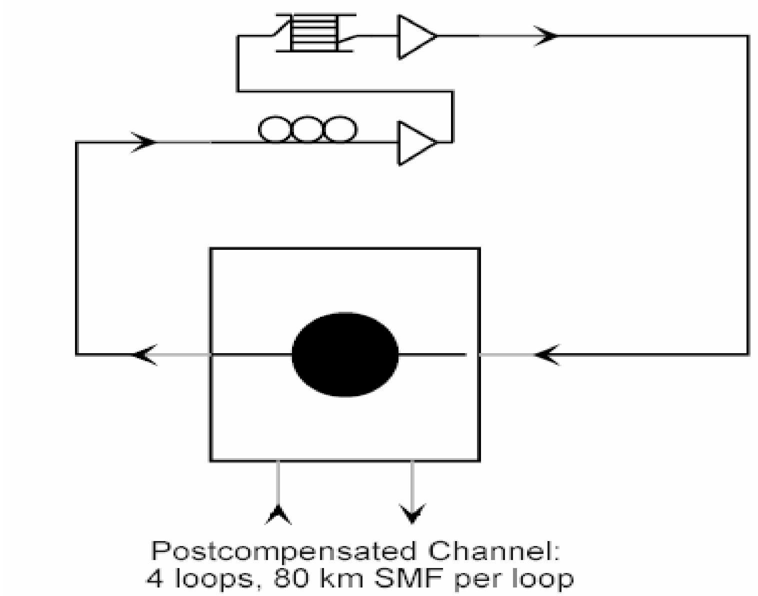

Figure 5.3: Post-compensation channel setup.

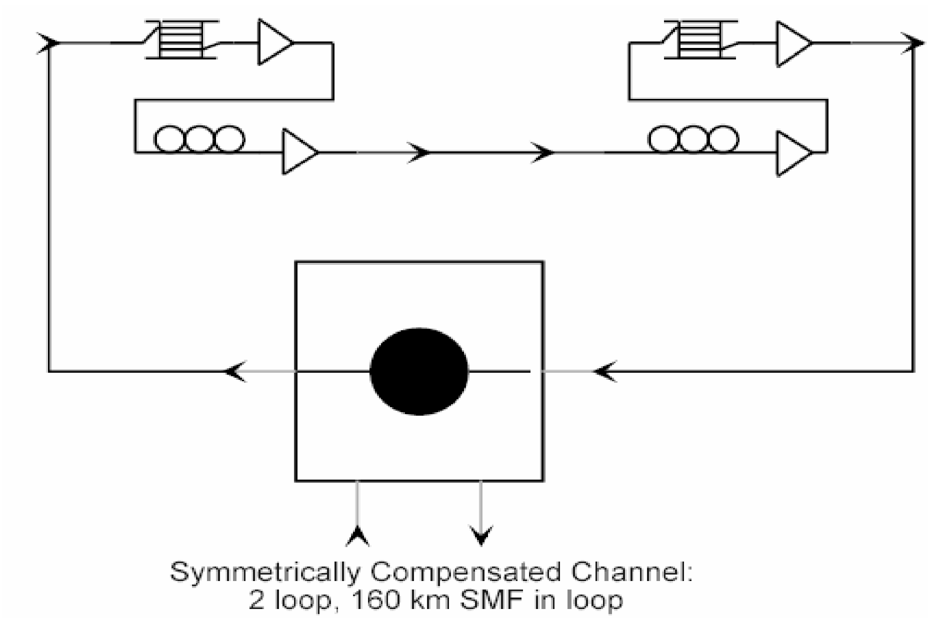

Figure 5.4: Symmetrical-compensation channel setup.

As shown in above figures (5.2 to 5.4), in pre- and post-compensation the DCFs are placed before or after the SMF fiber. In hybrid-compensation 50% of the SMF dispersion is compensated before the SMF and the other 50% is compensated afterwards. The system behaviour can be quite different for the different schemes because of the influence of dispersion compensation on the linear and nonlinear effects. A simplified approach to the definition of transparent sub networks divides each path in the network into a cascade of identical transmission sections, the so-called “normalized sections” [48, 49].

Defining the extension of transparent sub networks will be equivalent to finding the maximum number of normalized sections that can be cascaded for acceptable signal degradation. Normalized transmission sections consist of EDFAs, SMFs, and DCFs. Based on the ITU-T recommendations for terrestrial networks [50], span lengths of 80 km are considered. Due to the nonlinear nature of propagation, system performance depends on the power levels at the input of the different types of fibers, on the position of the DCF with respect to the SMF, and on the amount of residual dispersion. Three different types of spans have been considered and are shown in Figures above. They correspond to pre-compensation, where the DCF is placed before the SMF for each span, post-compensation, where it is placed after the SMF for each span, and hybrid split compensation, where the dispersion compensation is split into two sections of the equal dispersion amount placed before and after the SMF.

At first the setup is run without including fiber nonlinearities at 10 Gbps, and the results are observed by plotting the BER after implementing each compensation technique with respect to the input power at the x-y plotter. After that the setup is again run after including the nonlinear effects of the fiber, and the same plots are taken on the x-y plotter. The input power is varied from 2 mw to 10 mw in steps. The same procedure is repeated with varying the input power of the system. And then the results are analyzed to see the effect of power variation with nonlinearities of fiber for compensation technique.

To observe the performance of the three compensation techniques at higher bit rates with nonlinearities the bit rate of the CS-RZ transmitter is increased up to 40 Gbps. Plots are taken by going through the same procedure as described above.

5.3 Results and Discussions

In the previous sections, we discussed various components used in the simulation setup. Using this setup the measurements of BER of the three links at 10 Gbps and 40 Gbps with respect to the input power are taken. Results discussed below gives the comparison of the dispersion maps used to combat the nonlinear effects of the fiber. The comparison is done on the basis of BER versus input power for each compensation technique by changing the input power and bit rate of the input signal. It is observed that hybrid-compensation is better than that of pre and post compensation.

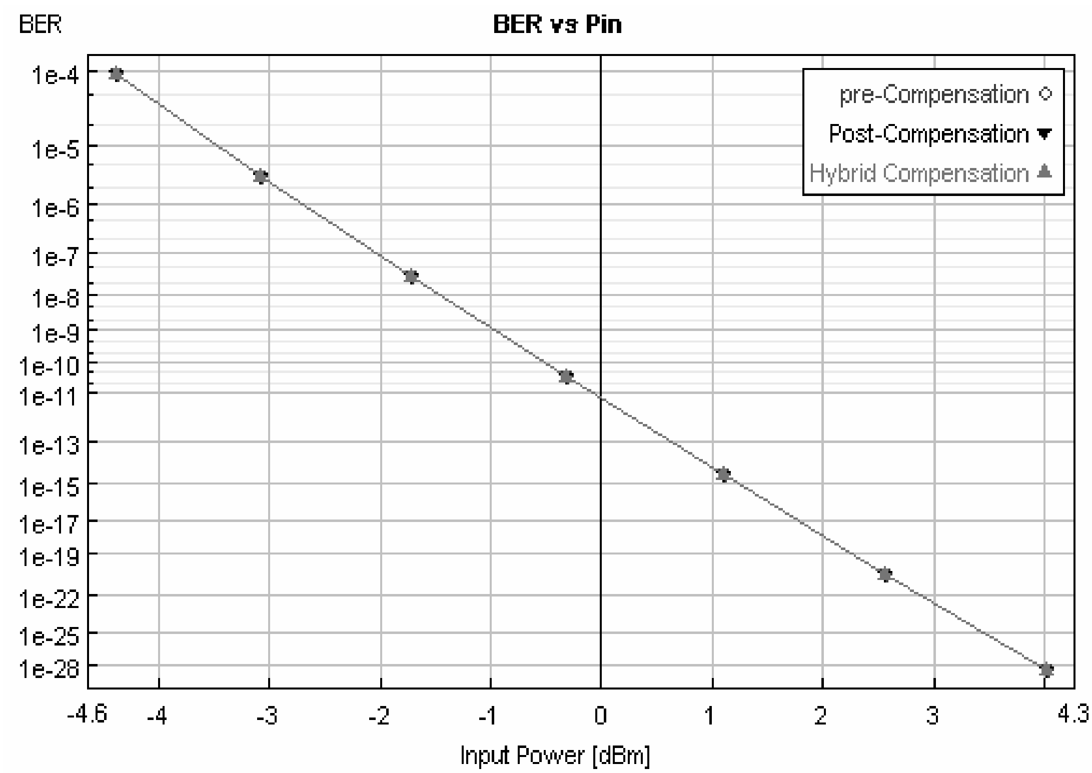

Figure 5.5: Comparison without nonlinearities at 10 Gbps with Pin 20mw.

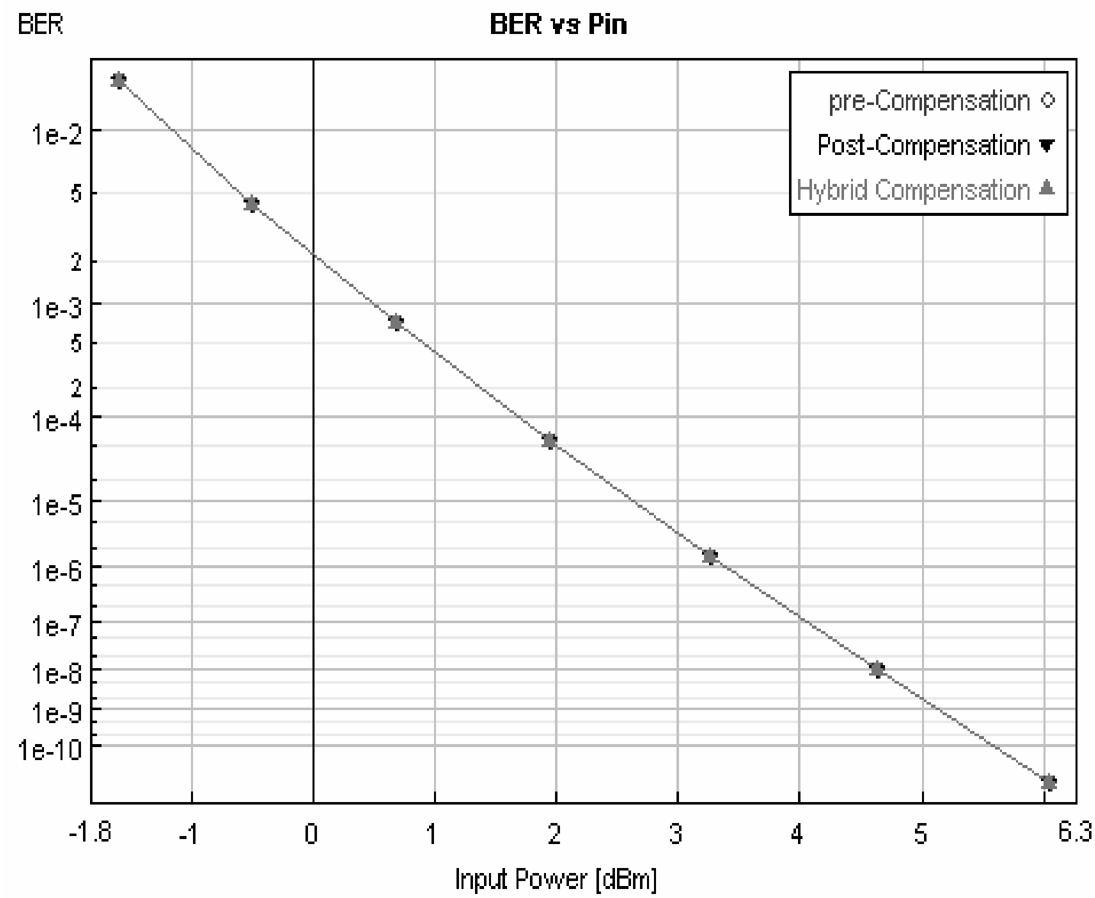

Figure 5.6: Comparison without nonlinearities at 40Gbps with Pin 20mw.

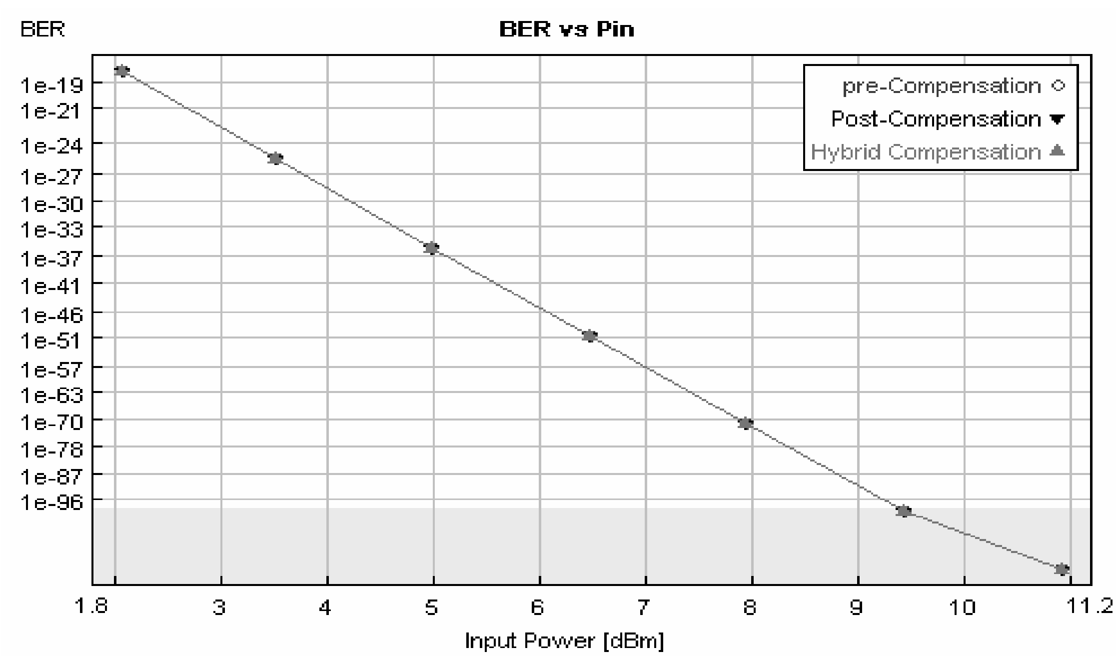

Figure 5.7: Comparison without nonlinearities at 10 Gbps with Pin 100mw.

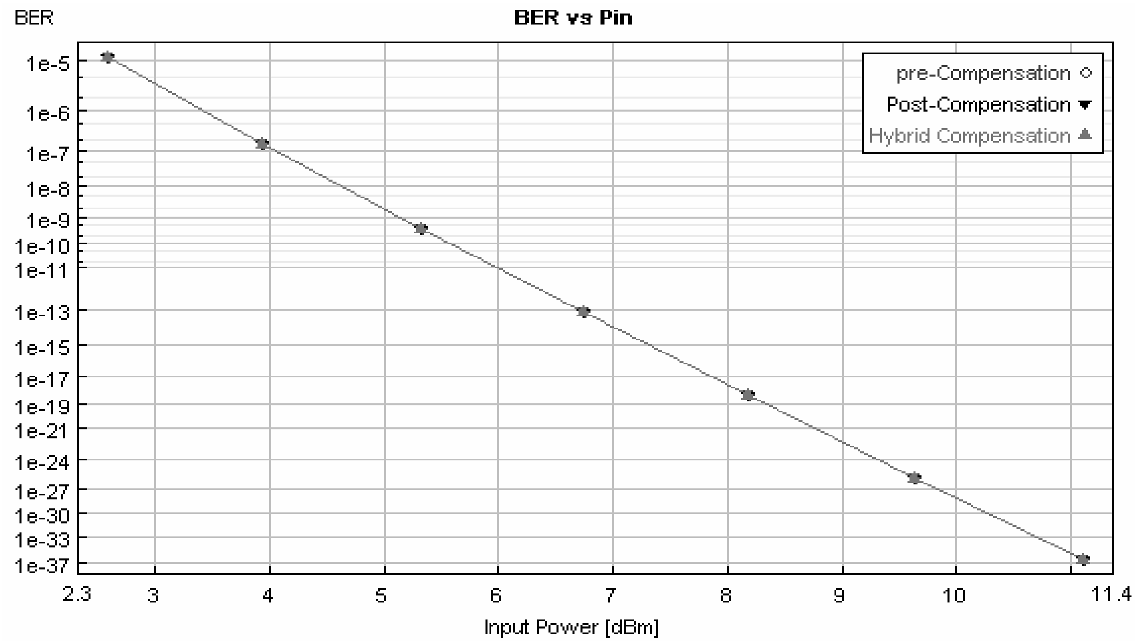

Figure 5.8: Comparison without nonlinearities at 40 Gbps with Pin 100mw.

The figures through (5.5 to 5.8) show the results of the runs at 20 mw and 100 mw with bit rates of 10 Gbps and 40 Gbps. Form the above plots it is found that in the absence of nonlinearities, performance of all the compensation techniques is almost same. Even it does not show any variation due to the variation of the power and the bit rate. But increase in the BER is observed in each plot for increase in input power and bit rate. At high input power the BER increases due to self phase modulation, which becomes dominant after a threshold signal power.

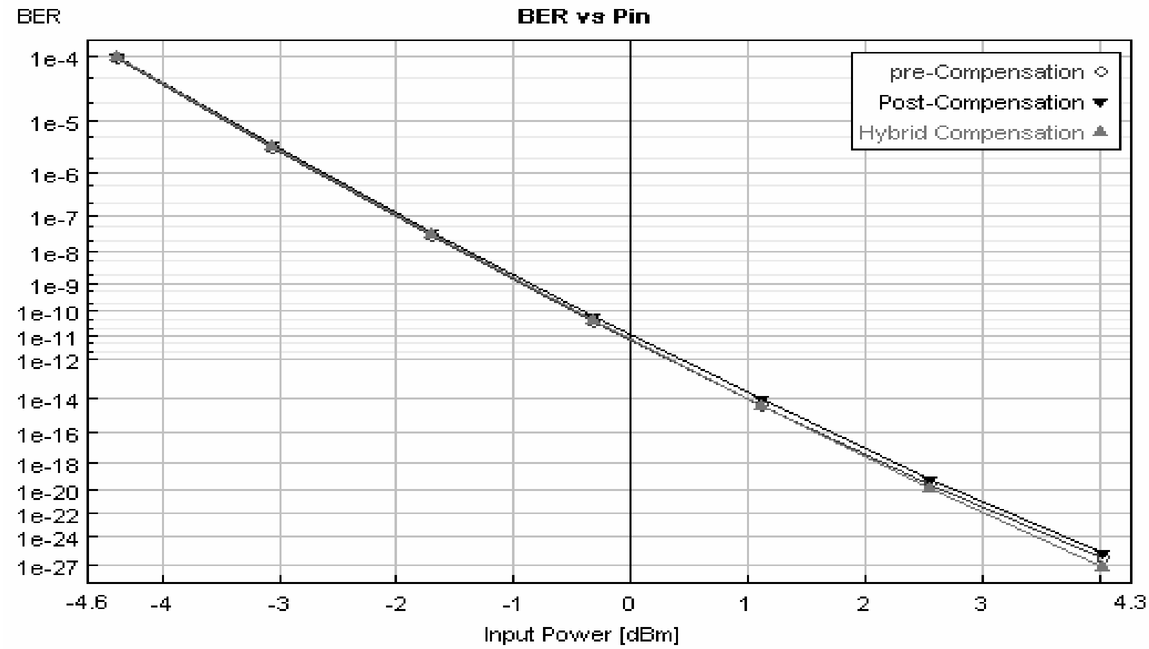

Figure 5.9: Comparison with nonlinearities at 10Gbps with Pin 20mw.

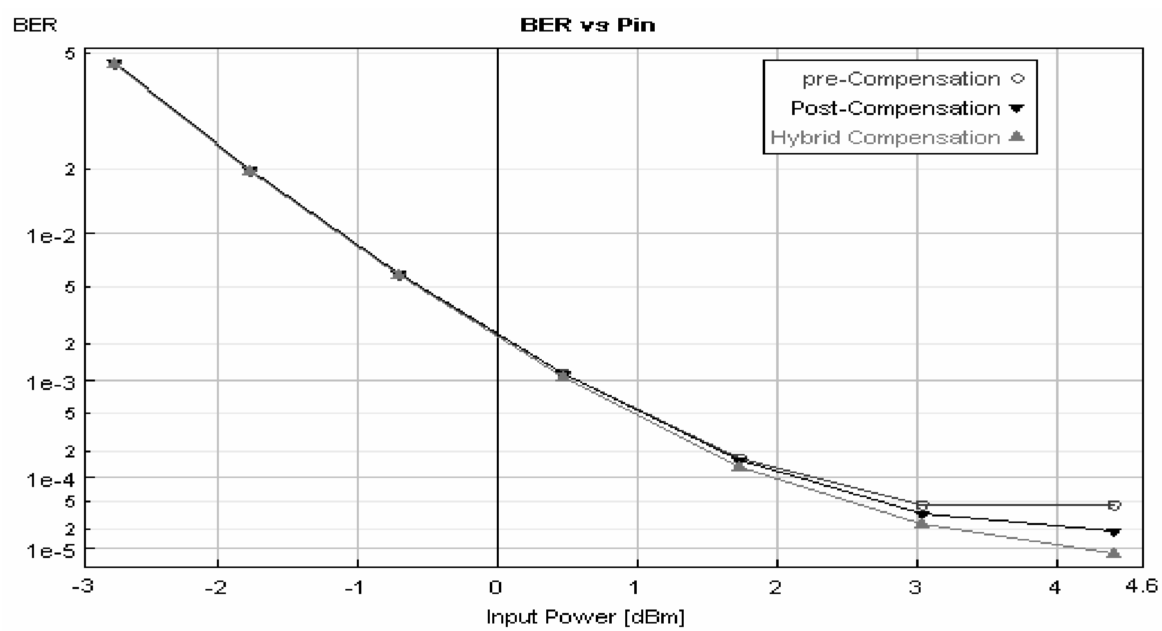

Figure 5.10: Comparison with nonlinearities at 40Gbps with Pin 20mw.

Figures (5.9) and (5.10) are describing the comparison of three compensation techniques. It can be seen from both plots that with the increase in input power the BER for all is decreasing. But the hybrid compensation is having the lowest BER as compared to the other two. The pre-compensation is having the higher BER than that of two and the post-compensation is showing the moderate BER at same input power level. It is observed that with the increase in input bit rate the BER also increases. But still the hybrid-compensation shows the lowers BER and the pre-compensation shows the highest BER.

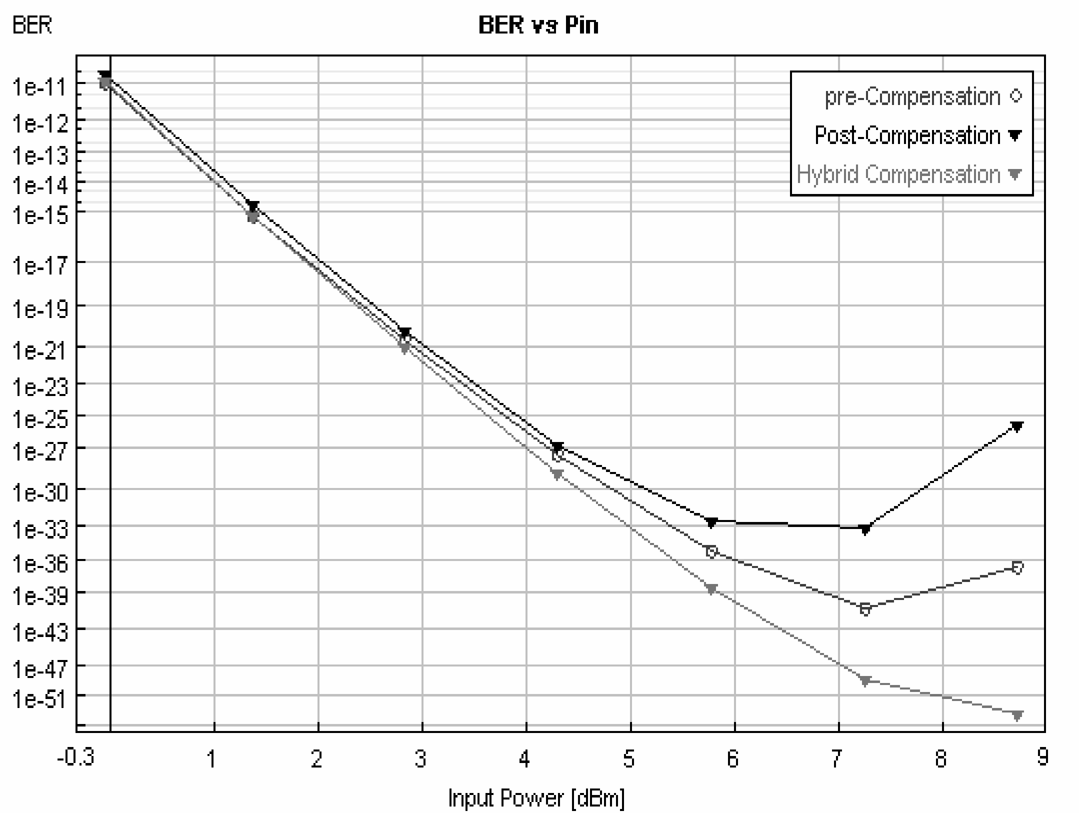

Figure 5.11: Comparison with nonlinearities at 10Gbps with Pin 60mw.

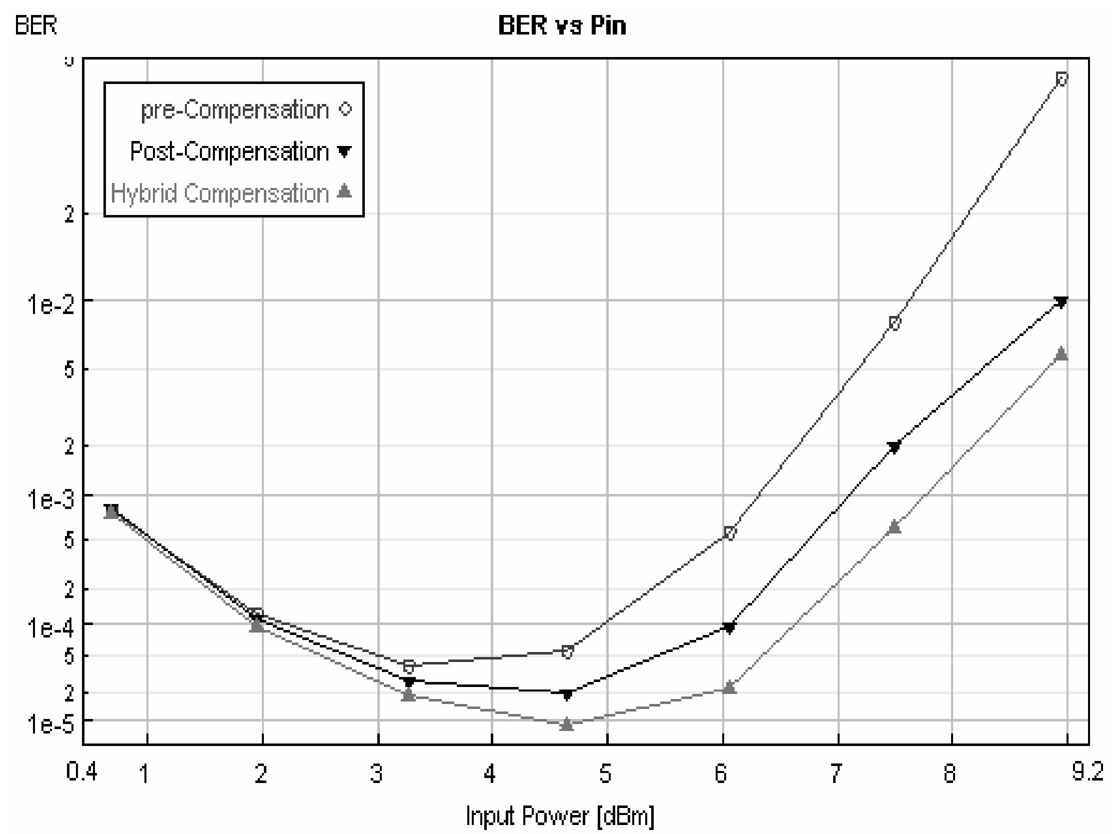

Figure 5.12: Comparison with nonlinearities at 40Gbps with Pin 60mw.

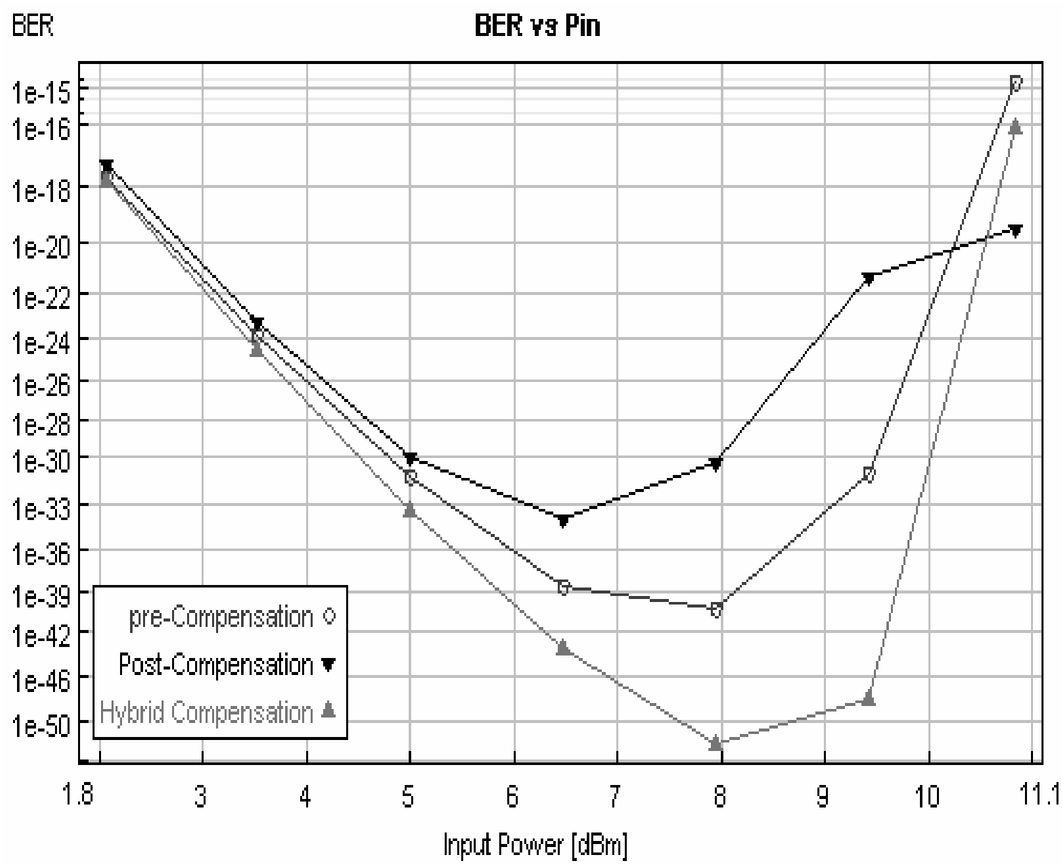

Figure 5.13: Comparison with nonlinearities at 10Gbps with Pin 100mw.

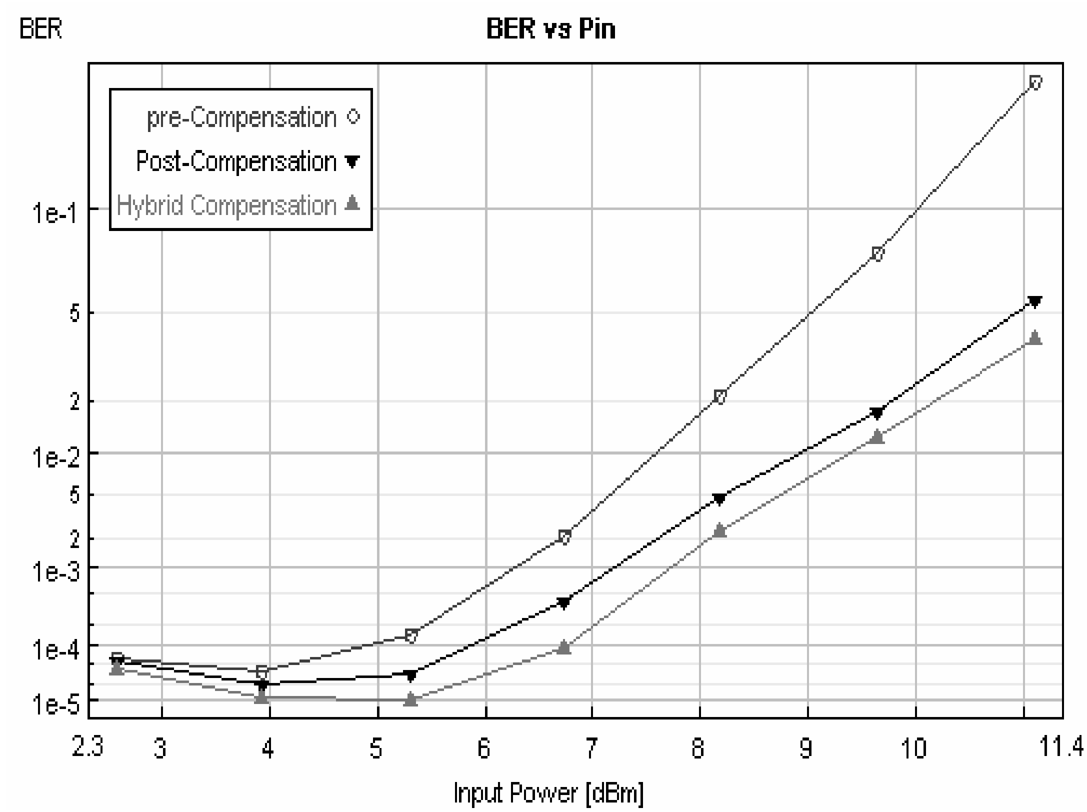

Figure 5.14: Comparison with nonlinearities at 40 Gbps with Pin 100mw.

Figures (5.11) and (5.12) shows the results of simulations run at 10 Gbps and 40 Gbps with input power 60mw respectively. The figures (5.13) and (5.14) show the results of simulation run at 10 Gbps and 40 Gbps with input power of 100mw. The results showing that as we are increasing the input bit rate the BER is increasing. The BER is also increasing with input power due to nonlinearities. But in all cases the hybrid-compensation shows the best results with lowest BER as compared to the other two.

4.4 Conclusion

After analysing all the results obtained, it is observed that the hybrid-compensation is the best in dispersion mapping. It reduces the BER produced by the fiber nonlinearities to the more extent than that of pre-compensation and the post-compensation. By using the hybrid-compensation the repeater length is increased almost up to double than that of pre and post-compensation. The pre-compensation shows the highest BER. It is also observed that with increase in the input bit rate the BER for all three compensation techniques is also increased. But the still the hybrid-compensation reduce the BER up to more extent. BER also increases with the increase in input optical power due to nonlinear impairments on the link at high powers.

Chapter-6 Conclusions

The work presented here is emphasized on the effects of Polarization Mode Dispersion (PMD) over the optical transmission system and the comparison of different Dispersion Maps.

6.1 Conclusions

The impacts produced by the increase of PMD are analyzed through eye diagrams and output power evaluation. The plots depict the values of eye opening, eye closing and output power for different values of PMD. Through the eye diagrams the output signal is observed at different values of PMD. It is well known that as the PMD increases the output electrical power decreases but as it can be seen in the above figures sometimes the electrical power increases, this is due to the effect of the dispersion on the PMD. Because linear effect of the dispersion compensates the nonlinear effects of the PMD of the fiber at some values of PMD the results are against the expectations. The effect of changing the value of PMD is reported in this chapter. It is reported that up to the PMD value of 20 $ps/\sqrt{km}$, the value of eye opening and output power decreased. It is studied that any further increase in value of PMD causes the great fluctuations in the characteristics of the measured parameters due to its random nature.

The bit rate limitations occurred due to PMD in high speed transmission systems are investigated by varying the bit rate for the specific values of PMD i.e. 2.5 $ps/\sqrt{km}$ and 0.1 $ps/\sqrt{km}$. The results describe that PMD puts the hurdles to move to higher data rates in the optical communication systems. It is reported that noticeable signal degradation starts from the data rate of 10 Gbps and becomes worst at 40 Gbps. It is also found in the results depicted by the plots that the link length variation (even more than 20 times) does not introduce any remarkable change in the effects of PMD.

The results of the fifth chapter describe the comparison of the pre, post and hybrid compensation maps. It is observed that hybrid compensation is better than its other counterparts. Making use of DCF in all of the compensation techniques, the results show that hybrid compensation gives more reduction in the BER due to the nonlinearities. The advantage of this approach is that the impact of nonlinearities in the transmission line can be significantly suppressed, because the pulses are fully dispersed during propagation. The input power limitations caused by the nonlinear impairments is also observed in the form of increased bit rate.

6.2 Future Scope

In this work, the limitations of PMD over higher data rates are studied. As there are different compensation techniques that have been available to mitigate PMD effects, but due to its unpredictable behaviour its effects cannot be suppressed completely. The further work can be extended by including the effects of PMD.

The dispersion maps are compared with fiber based compensation techniques. This work can be extended by using compensation devices like Fiber Bragg Grating and Optical Phase Conjugator.

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