Chapter 4

Signal Conditioning Parameters for OOFDM System

4.1 Introduction

The idea of SDR has been proposed for wireless transmission in 1980. Instead of relying on dedicated hardware, the network has capability of dynamically adapting itself to multi-user environment [109]. This chapter discusses the basics of SDOT utilizing dynamic adaptivity for performance improvement. Further, chapter discusses signal propagation through optical fiber and various impairments associated including attenuation, CD, PMD and non-linear effects. Next, importance of performance assessment for transmission system is introduced followed by various parameters that can evaluate system performance. This chapter simulates OOFDM system using Optsim and MATLAB. Further, various signal conditioning parameters including OSNR, Chromatic dispersion, PMD, electrical SNR, Channel noise, distortion of signal, group velocity dispersion, phase margin are reported. These parameters can be used for performance improvement, would form the base of subsequent chapters for performance enhancement.

4.2 Software Defined Optical Transmission

When light travel through fiber various impairments comes into picture that degrades system performance. Various techniques have been reflected by literature for compensating the effects of these impairments including optical compensation and electronic compensation. Optical compensation techniques using DCF is based on use of compensating fiber that negate the dispersion produced by optical link. These techniques require very precise match to be maintained between the slope of transmission link and DCF. Such matching can be achieved using fixed or tuneable optical grating [114, 115]. Further, to avoid disadvantages due to optical counterpart electronic compensation has been proposed in literature. Earlier stages of electronic compensation being based on
hardware utilization, make these techniques rigid, inflexible and show limited performance [113]. However, utilization of DSP for EDC can improve system performance significantly. SDOT allows dynamic adaptivity in which transponder can be made adaptable based on the channel conditioning parameters, like OSNR etc [111]. In particular, SDOT expect measurement of these conditioning parameters, that can be used for identifying fault and gaining adaptivity [112]. SDOT uses DSP to modify rigid, inflexible optical network to flexible and robust network, capable of adapting to various standards or modulation formats [34]. Usage of SDOT lessens the maintenance and operational costs. Fig.4.1 represents block diagram for implementing SDOT.

![Fig. 4.1. Diagram representing Software Defined Optical Transmission (SDOT) [34].](image)

Architecture represents the utilization of DSP power for adaptation and reconfiguration to appropriate modulation formats. EDC via DSP can improve the system performance considerably by enhancing tolerance against channel impairments [111]. In order to attain an eventual target of BER optical transmission has to be designed for reliable operation [34]. This demands the management of important communication parameters including channel impairments etc. Proper designing of optical transmission system expect management of all different parameters that degrade system performance. The most important parameter for measuring the transmission quality is SNR that is
defined as ratio of signal power to noise power to be determined at decision point. BER a figure of merit of transmission system is defined as the ratio of bits in error to total number of transmitted bits at the decision point [116].

4.3 Signal Propagation through Optical fiber

The main target of optical transmission system is to transmit signal $E(t,z)$ from transmitter to receiver such that transmitted signal $E(t,0)$ at transmitting end has similarity with received signal $E(t,z_{end})$ at receiver end. The propagation of optical field $E(t,z)$ through optical fiber is described using non-linear Schrödinger equation (NLSE) as in eq. (4.1)[117]:

$$\frac{\partial E}{\partial z} = -j \frac{\beta_2}{2} \frac{\partial^2 E}{\partial t^2} + j \gamma |E|^2 E = \frac{\alpha}{2} E$$  (4.1)

Where $E$ represent electric field, $\alpha$ the attenuation constant represents the attenuation that affects signal power, $\beta_2$ represents dispersion parameter, $\gamma$ represents non-linear coefficient, $z$ and $t$ represent propagation direction and time [117]. Each term on the right side of eq. 4.1 represents impairments that produces signal distortion.

In order to achieve error free transmission the effects of these impairments need to be compensated. The term corresponding to signal power $|E|^2$ in above equation, represent non-linear effects. Degradation in the system performance is produced due to non-linearities if launched power is increased for enhancing SNR [117]. Hence, there is requirement to study the linear and non-linear effects that degrade system performance for improving system performance.

4.4 Linear Effects

4.4.1 Distortion

As the signal propagates through optical fiber, it is distorted. The reason for its occurrence is that amplitude response of optical fiber is not constant and phase response is non-linear. Thus, distortion of signal is contributed due to attenuation
that leads to loss of signal as it propagates through fiber and dispersion that occurs as different wavelengths and modes travel through fiber at different speeds.

### 4.4.1.1 Attenuation

When signal propagates through optical fiber reduction in power level is produced due to attenuation. The attenuation effects can be described as eq. (4.2):

$$|E(t, z)|^2 = |E(t, 0)|^2 e^{-az} \quad (4.2)$$

Where, $|E(t, 0)|^2$ represents power at input stage and $|E(t, z)|^2$ power at distance $z$ [118]. As the power propagates along fiber, it undergoes reduction in its level. This reduction can be beaten by using periodic optical amplifier along the length of fiber. Attenuation of power in optical fiber is propagating wavelength dependant. Attenuation of order 0.2 dB/km has been reported for wavelength 1.55 µm [118].

### 4.4.1.2 Chromatic Dispersion (CD)

CD can be depicted as broadening of optical signal when, it is inserted in dispersive optical fiber. It occurs because different spectral components propagate at different speed. A relative delay among different frequency components produces distortion in signal. As a result, ISI is produced due to interference among neighbouring bits causing degradation in signal. The main reason for this occurrence can be described as in eq. (4.3):

$$\beta(\omega) = n(\omega) \frac{\omega}{c} \quad (4.3)$$

Where $\beta(\omega)$ is mode propagation constant, $n(\omega)$ is wavelength dependent refractive index, $\omega$ is angular frequency and c is speed of light [119]. Taylor series expansion of $\beta(\omega)$ can be expressed as in eq. (4.4) [119, 236]:

$$\beta(\omega) \approx \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \frac{1}{6}\beta_3(\omega - \omega_0)^3 + \cdots \quad (4.4)$$

Where the term corresponding to $\beta_0$ is constant phase shift, second term $\beta_1$ represents the speed at which envelope propagates, third term $\beta_2$ represents group velocity dispersion (GVD) which is change in velocity as function of angular frequency, fourth term $\beta_3$ represents change in GVD with angular frequency.
Thus, the dispersion parameter $D$ representing chromatic dispersion obtained from second derivative $\beta_2$ can be defined as in eq. (4.5) [119]:

$$D(z) = -\frac{2nc}{\lambda^2} \beta_2(z)$$ (4.5)

Where $\lambda$ represents wavelength and $c$ is speed of light. Ignoring the effects of attenuation and non-linearities in eq. (4.1), the effect of chromatic dispersion on envelope of $E(z, t)$ can be described as in eq. (4.6):

$$\frac{\partial E(t, z)}{\partial z} = -j \beta_2 \frac{\partial^2 E}{\partial t^2}$$ (4.6)

Where $z$ represents propagation distance, $t$ time interval, $\beta_2$ represents GVD frequently called as dispersion. In frequency domain, the solution of eq. (4.6) can be expressed as eq. (4.7):

$$E(\omega, z) = E(\omega, 0) e^{j\beta_2 \omega^2 z}$$ (4.7)

It can be inferred from frequency domain expression, eq. 4.7 that chromatic dispersion produces phase shift leading to broadening of the pulse.

### 4.4.1.3 Polarization Mode Dispersion

In optical transmission, the propagating field can be described using two orthogonal polarizations. Output is produced by degeneration of both polarizations. Practical optical fibers are non-symmetric as their structure is not perfectly symmetric due to mechanical tension, thermal gradients etc. This leads to non-degeneration in two orthogonal fields, as they are not degraded equally.

The two polarization exhibit different velocities as they observe different refractive index leading to differential group delay (DGD). This DGD produces broadening in pulse leading to PMD [121]. DGD is measured as difference between arrival time of two polarizations.

The relation between DGD and PMD can be expressed as eq. (4.8):

$$\Delta \tau = PMD \cdot \sqrt{L}$$ (4.8)

Where PMD parameter has value varying between 0.01 and 0.5ps/$\sqrt{km}$ and $L$ represents length of fiber in km.
4.4.2 Amplified Spontaneous Emission Noise

Noise, being the most important degradation effect in optical communication system can have origin at various levels. Lasers, optical channel, optical connectors, optical splices, optical detectors can contribute to various forms of noises. Optical amplifiers contribute spontaneous emission noise that get amplified and thus known as amplified spontaneous-emission noise (ASE). Although the attenuation of the signal propagating through optical fiber is very small compared to other transmission media like copper cable or wireless channel, but the amplification of attenuated signal in optical domain is very important for restoring the signal. This amplification can be achieved using optical amplifiers based on stimulated emission through population inversion. Erbium doped fiber amplifier (EDFA) has been preferred for amplification as they provide high gain. However, EDFA becomes dominant source of noise in optical transmission system. Spontaneous emission phenomenon generates ASE noise added at every amplifier stage and degrades system performance. Thus, ASE noise constitutes the most severe impairment limiting reach and capacity [120, 123]. The effect of noise can be described using noise figure (NF) which is defined as ratio of SNR at the input to SNR at the output [122] and can be expressed as eq. (4.9):

\[
NF = \frac{SNR_{in}}{SNR_{out}} = \frac{P_{\text{sig}}/P_N}{G \cdot P_{\text{sig}}/(P_N + P_{\text{ASE}})}
\]  

(4.9)

Where, \( P_{\text{sig}}/P_N \) represents ratio of signal power to noise power at input, \( G \) is amplifier gain, \( P_{\text{ASE}} \) is ASE power added by EDFA. \( P_{\text{ASE}} \) can be expressed as eq. (4.10) [123]:

\[
P_{\text{ASE}} = 2\eta_{\text{sp}}(G - 1)hv\Delta\nu
\]  

(4.10)

Where \( \eta_{\text{sp}} \) represents spontaneous factor, \( h \) is Planck’s constant, \( G \) represents amplifier gain and \( \Delta\nu \) is bandwidth. \( \eta_{\text{sp}} \) Spontaneous factor can be represented as eq. (4.11) [123]:

\[
\eta_{\text{sp}} = \frac{NF \cdot G}{2(G-1)}
\]  

(4.11)

For high gain the value of NF can be approximated to \( \approx 2\eta_{\text{sp}} \). OSNR can be considered for characterizing signal spontaneous noise impairment. OSNR is defined as ratio of signal power to ASE power in specified optical bandwidth.
Target OSNR can be defined as the value of OSNR that is expected to attain performance of determined level. Usually, performance may be defined in terms of BER whose value for commercial systems these days is set to be as $10^{-15}$ for error free transmission [123]. It is expected that target OSNR should be capable of providing sufficient margin for various channel impairments including chromatic dispersion, PMD, non-linearities, distortions, amplifier noise, against variances in performance of transmitter and receiver components due to designing faults, against aging effects of components. A theoretical increase in the value of target OSNR has been reported by 6 dB for each increase in channel bit rate with factor of 4 for achieving same noise performance [123].

At the higher bit-rates, the effects of impairments become severe making it difficult to maintain performance level. So the increase on target OSNR with rise of bit rate become more then above stated value. Further, an increase in transmission distance results increase in the number of amplifiers that increases the contribution due to ASE and finally results to decrease in the value of OSNR at the end. The well management of transmission impairments allows to attain maximum un-regenerated reach, that is defined as the length at which target OSNR for achieving desired performance is equal to OSNR at the end. This maximum reach length depends on the fiber and amplifier characteristics.

### 4.5 Non-linear Effects

The effect of non-linearities comes into picture when high intensity electromagnetic field interacts with silica electrons. The effect of non-linearities can be described as eq. (4.12) [119]:

$$E(t, z) = E(t, 0)e^{i\phi_{NL}(t, z)}$$  \hspace{1cm} (4.12)

Where $\phi_{NL}$ represents non-linear phase shift caused by self phase modulation (SPM) leading to widening of spectrum [119]. $\phi_{NL}$ can be expressed as in eq. (4.13):

$$\phi_{NL} = \gamma |E(t, 0)|^2 L_{ef}$$  \hspace{1cm} (4.13a)

$$L_{ef} = \frac{1-e^{-\alpha z}}{\alpha}$$  \hspace{1cm} (4.13b)
Where $A_{ef}$, $L_{ef}$ are effective core area and length of fiber, $\lambda$ represents wavelength, $n_2$ is refractive index [236]. Further, Wavelength division multiplexing (WDM) transmission involves various channels. Phase shift produced in particular channel is affected by power of neighbouring channel also and this phenomenon is called cross phase modulation (XPM). Phase shift produced in this process can be expressed as eq. (4.14) [119]:

$$\Phi_{NL} = \gamma L_{ef} |E_n(0)|^2 + 2 \sum_{i=1,i\neq n}^{N} |E_i(t)|^2$$  \hspace{1cm} (4.14)

$|E_n(0)|^2$ is power associated with $n^{th}$ channel. Another non-linear effect, which is again result of composite optical transmission, is known as four wave mixing (FWM). It can be defined as phenomenon where different carrier frequencies interact to produce new frequency expressed as eq. (4.15):

$$f_{mnbk} = f_m + f_n - f_k + f_l$$  \hspace{1cm} (4.15)

Non-linear effects involved for single channel transmission are discussed in subsequent chapters.

### 4.6 Transmission System Performance Assessment

Performance monitoring is very significant for controlling and delivering desired quality service to end user. There are various parameters that can be used as figure of merit for estimating transmission quality including SNR, OSNR and BER etc. SNR at the judgement end may be defined as ratio of signal power to noise power. As discussed before, amplification is associated with accumulation of ASE noise. OSNR is defined as ratio of optical power to accumulated noise power at receiver. It is very important to achieve minimum target OSNR at the receiver to attain desired performance. OSNR can be expressed as eq. (4.16) [34]:

$$OSNR = \frac{P_{sig}}{P_{ASE}} = \frac{P_{sig}}{(N_{amp} L_{\text{span}} NF) \frac{hc}{\lambda} \nu \nu}$$  \hspace{1cm} (4.16)

Where $P_{sig}$ is output signal power, $P_{ASE}$ is amplifier noise, $\nu \nu$ is bandwidth. In right of eq. 4.16, amplifier noise is expressed in terms of $N_{amp}$ represent to total number of fiber spans, $L_{\text{span}}$ is loss of each span, noise figure ($NF$), $c$ and $\lambda$ being
speed and wavelength of light. Considering more specific case, with wavelength of 1.55 \( \mu m \) and optical bandwidth by convention, which is usually taken to 0.1nm and transform the eq. (4.16) to logarithmic domain expression, OSNR at the end can be approximated as (4.17) [123, 237]:

\[
\text{OSNR (in dB)} = 58 + P_{\text{sig}}(dB) - L_{\text{span}}(dB) - NF(dB) - 10\log (N_{\text{amp}}) \quad (4.17)
\]

Eq. (4.17) defines the constraints imposed by noise in long haul system designing. An increase in value of available OSNR results in increase in maximum reach length. This increase may be achieved either by increasing \( P_{\text{sig}} \), or with decrease of \( NF \), or with decrease of \( L_{\text{span}} \) or with decrease in number of spans.

BER an important parameter for quality evaluation is defined as ratio of number of bits in error to total numbers of bits transmitted. This parameter gives the measure of probability for a bit to be mistakenly detected by decision circuit. Theoretical expression for BER in case of M-ary QAM can be expressed as eq. (4.18) [124, 126]:

\[
\text{BER} \equiv \frac{\sqrt{M-1}}{\sqrt{M} \log_2 M} \cdot \text{erfc} \left( \sqrt{\frac{3 \log_2 M \cdot \text{SNR}}{2(M-1)}} \right) \quad (4.18)
\]

where \( \text{erfc}(\chi) \) is complementary error function. Error vector magnitude (EVM) an another common parameter for evaluating quality of received signal is calculated by subtracting received signal and transmitted reference signal. It gives the measure of deviation of received signal [125]. In the system, involving OFDM system EVM can be evaluated by comparing transmitted symbols that are input to IFFT and received demodulated symbols that are obtained after FFT.

![Fig. 4.2: Error Vector Magnitude between Measured and reference Signal](image-url)
EVM is represented by figure 4.2. Root mean square (RMS) value of EVM for M-OFDM transmitted symbols can be expressed as eq. (4.19) [126]:

\[
EVM_{rms} = \sqrt{\frac{1}{M} \sum_{i=1}^{M} \left| \frac{S_{i,r} - S_{i,m}}{\frac{1}{M} \sum_{i=1}^{M} |S_{i,r}|^2} \right|^2}
\]  

(4.19)

Where \(S_{i,r}\) is reference symbol and \(S_{i,m}\) is measured symbol. We can modify equation 4.19 in terms of in phase and Quadrature components as eq. (4.20):

\[
EVM_{rms} = \sqrt{\frac{1}{M} \sum_{i=1}^{M} \left[ \left| S_{I,(r)}A_m - S_{I,(m)}A_k \right|^2 + \left| S_{Q,(r)}A_m - S_{Q,(m)}A_k \right|^2 \right]} \frac{1}{p_{av}}
\]  

(4.20)

Where \(S_{I,(r)}\) and \(S_{I,(m)}\) represents in-phase reference and measured values, \(S_{Q,(r)}\) and \(S_{Q,(m)}\) represents quadrature reference and measured values, \(A_m\) and \(A_k\) are scaling factors. Further Eq. 4.20 can be represented as eq. (4.21):

\[
EVM_{rms} = \sqrt{\frac{1}{M} \sum_{i=1}^{M} [N_{I,(r)} + N_{Q,(r)}]^2} \frac{1}{p_{av}}
\]  

(4.21)

Where \(N_{I,(r)}\), \(N_{Q,(r)}\) represents in-phase and quadrature noise components. Further, EVM can be related to SNR as eq. (4.22):

\[
EVM_{rms} = \sqrt{\frac{1}{SNR}}
\]  

(4.22)

Following above discussion eq. (4.18) can be expressed as [126, 244]:

\[
BER \cong \frac{\sqrt{M-1}}{\sqrt{M} \log_2 \sqrt{M}} erf c \left[ \frac{1}{EVM} \sqrt{\frac{3 \log_2 M}{2(M-1)}} \right]
\]  

(4.23)

Analytical expression eq. (4.23) evaluates BER using EVM that may not be possible at high data rates due to memory and restrictions of MATLAB.

In OOFDM system beside BER, SNR, Quality (Q) factor is another important parameter that can be used as performance metric for measuring transmission quality. This parameter can be extracted for monitoring communication link performance and varying network parameters for gaining adaptivity and improving system performance. Q factor as figure of merit with respect to optical transmissions is defined as eq. 4.24:

\[
Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0}
\]  

(4.24)
Where $I_0, I_1$ are average photocurrents for symbol zero and symbol one levels and $\sigma_0, \sigma_1$ represents the standard deviations.

4.7 Simulation Setup

Fig 4.3 represents schematic using DD-OOFDM system. The design consists of three main parts; OFDM transmitter, optical fiber for transmission and OFDM receiver. MATLAB is used to transmit, receive OFDM signals and simulation setup is using Optsim platform for optical fiber transmission. One very important feature of Optsim is its co-simulation capability in which it can co-simulate with various softwares like MATLAB and Cadence etc. This feature helps to create customized component for MATLAB (CCM) that can be used by Optsim to simulate in optical environment. MATLAB subroutine controls the functionality and behaviour of CCM by pre-processing and post-processing [127]. This feature is exploited in this thesis for simulating OOFDM system. In order to perform various performance analyses different parameters associated with CCM can be easily altered. These parameters may include change in number of bits, or modulation format, or size of IFFT/FFT, or number of subcarriers for OFDM systems.

MATLAB subroutine acting as transmitter produces OFDM signal that is interfaced with Optsim. Further, another MATLAB subroutine act as receiver and performs demodulation of OFDM symbol, error calculation. Real valued OFDM

![Fig. 4.3: Model for direct detection OOFDM system](image-url)
signal is generated in MATLAB using RF up-conversion that mixes baseband complex signal with RF signal. Real valued generation is expressed as eq. (4.25):

\[ s_{up}(t) = Re\{s(t)\} \cos(2\pi f_c t) - Im\{s(t)\} \sin(2\pi f_c t) \]  

(4.25)

Where \( s(t) \) represents complex baseband signal \( f_c \) carrier frequency, \( s_{up}(t) \) represent real valued up converted electrical OFDM signal. OFDM signal is produced using 64 subcarriers, 16 QAM at data rate of 18.4 Gb/s. Cyclic prefix extension has been used 25% i.e 16 samples.

Table 4.1 summarizes important simulation parameters used in this chapter. After electrical OFDM signal has been generated by MATLAB subroutine, the signal passes to Optsim platform. In this work external modulation, Mach-Zehnder modulator (MZM) is used to convert electrical signal to optical signal. A CW Lorentzian laser with 0.50 mW (-3 dBm) output power, 1550 nm centre emission wavelength has been used as optical source.

<table>
<thead>
<tr>
<th>System Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcarrier modulation format</td>
<td>16-QAM</td>
</tr>
<tr>
<td>Samples per bit</td>
<td>4</td>
</tr>
<tr>
<td>FFT size</td>
<td>64</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>64</td>
</tr>
<tr>
<td>Cyclic prefix</td>
<td>16</td>
</tr>
<tr>
<td>Net data rate</td>
<td>18.4 Gb/s</td>
</tr>
</tbody>
</table>

OOFDM signal is the passed through optical link using SMF. In order to overcome the attenuation of SMF optical amplifier has been inserted in each span of fiber link. After photo-detection of electrical signal at the receiver using PIN photodiode Optsim further invokes the MATLAB subroutine and passes the control to MATLAB for digital signal processing, demodulation, de-mapping and BER calculation etc. As the main purpose of this research is to improve system performance based on certain signal conditioning parameters so the parameters shown in table 4.1 are not fixed values but these values like number of subcarriers, cyclic prefix size, modulation format etc is varied in subsequent chapters for analysing and enhancing system performance. In optical transmission although both linear and non-linear characteristics of fiber put restriction on high
speed communication but this chapter consider the effects of linear characteristics including CD, PMD, OSNR and ignores the effects of non-linearities. The non-linearities are dealt in subsequent chapters. This chapter reports various linear transmission impairments along with various channel-conditioning parameters.

An expectation to obtain proper communication through optical channel is transmission without distortion and loss. The propagation of light through optical fiber is accompanied by loss (attenuation) which increases with distance. So it becomes very important to use amplifier with suitable gain to compensate the loss effects. This work is using EDFA with suitable gain for compensating the effect of losses. Further, in addition to amplification the use of EDFA makes another major contribution to channel noise in the form of ASE noise, which degrades the system performance thus increasing BER. On an assumption that major contribution to channel noise is due to ASE noise, the effect of channel noise can be quantified using Noise figure and OSNR where OSNR is ratio of signal power to ASE power in specified optical bandwidth. The target performance can be achieved if OSNR is sufficient enough to deal with channel impairments. In-line optical amplifier is having output power of 3.98 mW (6 dBm), corresponding $OSNR(\text{in dB})$ is be approximated using eq. 4.17. During noise analysis, simulation is carried over optical link using fiber of 200 km with attenuation of 0.2 dB/km, dispersion 16 ps/nm/km, dispersion slope 0.0593 ps/nm$^2$/km. Among various factors effecting OSNR that include output power of amplifier, span loss, number of spans are assumed constant and effect of change in NF has been tabulated in table 4.2. Further, to have more clear interpretation OSNR is calculated and corresponding eye-closure measurements, BER are tabulated. Increase in noise results an increase in the value of eye closure.

<table>
<thead>
<tr>
<th>Noise figure (dB)</th>
<th>OSNR (dB)</th>
<th>Eye-closure</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>19.5</td>
<td>0.0003756</td>
<td>$3.456e^{-05}$</td>
</tr>
<tr>
<td>6.5</td>
<td>17.5</td>
<td>0.0004679</td>
<td>$1.2678e^{-04}$</td>
</tr>
<tr>
<td>7.5</td>
<td>16.5</td>
<td>0.0006265</td>
<td>$2.344e^{-03}$</td>
</tr>
</tbody>
</table>
Rise in noise figure value from 4.5 dB to 7.5 dB describes increase in noise effect, that produces fall in OSNR value from 19.5 dB to 16.5 dB. This is reflected by increase in BER value from $0.3456e^{-05}$ to $1.2678e^{-04}$ to $0.2344e^{-03}$ and corresponding rise in eye closure from 0.0003756, to 0.0004679, to 0.0006265. This can be attributed to the fact that as there is rise in noise, there is increase in number of errors thus reducing eye opening and producing rise in error rate.

The distortion produced in optical transmission can be observed through pulse broadening. The major causes of distortion in optical transmission include intermodal dispersion, intra-modal dispersion (including chromatic dispersion and polarization mode dispersion). The main reason for occurrence of these dispersions can be attributed to the fact that different spectral components and orthogonal polarizations of light behave differently leading to distortion. In single mode fiber, the main contribution to distortion is due to CD and PMD. This work is using SMF for optical transmission so distortion effect is reported due to CD and PMD. Transmission performance is degraded due to dispersion. BER can be used as performance metric for measuring distortion. Thus, in this chapter linear
distortions including CD, PMD and GVD is reported using BER and Q factor as performance metric for OOFDM system. One very interesting feature provided by Optsim is disabling the effects of physical parameters like dispersion, PMD, non-linearity so that their effects can be studied individually [127]. In order to analyse
the effect of PMD the effect of other impairments like dispersion, non-linearities is kept off during simulation. This is obtained by turning off Raman effects, Raman self-interaction, SPM, XPM, dispersion effects, attenuation is disabled by making loss parameter zero. Analysis of variation of Q over different PMD values has been carried over 16-QAM-OOFDM, 64-QAM-OOFDM and 256-QAM-OOFDM system. Fig. 4.4 represents variation in value of Q over different value of PMD using 16-QAM-OOFDM system, whereas fig.4.5 represents it over 64-QAM-OOFDM system and fig.4.6 represents 256-QAM-OOFDM system. 16-QAM-OOFDM system reports Q factor 20.5 dB for 0.1ps/√km PMD, 14.5 dB for 0.3ps/√km PMD, 13 dB for 0.5ps/√km PMD at 150 km. 64-QAM-OOFDM system reports Q factor 14 dB for 0.1ps/√km PMD, 11 dB for 0.3 ps/√km PMD, 7.5 dB for 0.5 ps/√km PMD at distance of 150 km. 256-QAM-OOFDM system reports Q factor 12.5 dB for 0.1ps/√km PMD, 9.5 dB for 0.3 ps/√km PMD, 6.2 dB for 0.5 ps/√km PMD at distance of 150 km. An increase in modulation order from 16-QAM to 64-QAM to 256-QAM has lowered the Q factor at same distance. This can be attributed to the fact as the modulation order increases the energy efficiency decreases, so higher modulation order reports lower Q factor. Table 4.3 summarizes measurement of distortion over varying PMD value to 0.1, 0.3, 0.5 ps/√km in terms of Q and BER values obtained from electrical scope at 150 km for 16-QAM, 64-QAM and 256-QAM OOFDM system. An increase in PMD value from 0.1 ps/√km, 0.3 ps/√km to 0.5 ps/√km results in degradation of Q factor and corresponding rise in BER values for each modulation order.

<table>
<thead>
<tr>
<th>PMD value(ps/√km)</th>
<th>Modulation Order (M)</th>
<th>Q value (dB)</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>16-QAM</td>
<td>20.5</td>
<td>0.5638e⁻⁰⁹</td>
</tr>
<tr>
<td>0.3</td>
<td>16-QAM</td>
<td>14.5</td>
<td>0.3482e⁻⁰⁸</td>
</tr>
<tr>
<td>0.5</td>
<td>16-QAM</td>
<td>13</td>
<td>1.263e⁻⁰⁶</td>
</tr>
<tr>
<td>0.1</td>
<td>64-QAM</td>
<td>14</td>
<td>0.2471e⁻⁰⁷</td>
</tr>
<tr>
<td>0.3</td>
<td>64-QAM</td>
<td>11</td>
<td>0.4369e⁻⁰⁶</td>
</tr>
<tr>
<td>0.5</td>
<td>64-QAM</td>
<td>7.5</td>
<td>0.87627e⁻⁰⁵</td>
</tr>
<tr>
<td>0.1</td>
<td>256-QAM</td>
<td>12.5</td>
<td>0.23e⁻⁰⁶</td>
</tr>
<tr>
<td>0.3</td>
<td>256-QAM</td>
<td>9.5</td>
<td>2.46e⁻⁰⁵</td>
</tr>
<tr>
<td>0.5</td>
<td>256-QAM</td>
<td>6.2</td>
<td>3.56e⁻⁰⁴</td>
</tr>
</tbody>
</table>
This can be attributed to the fact that an increase in the value of PMD coefficient increases un-correlation between the two polarization components. As the un-correlation becomes prominent, there is rise in the value of differential group delay (DGD) and thus reduction in Q factor [128].

![Graph showing Q value variation for different CD values.](image1)

**Fig. 4.7:** Variation of Q over 15, 16, and 18 ps/nm/km CD values for 16-QAM-OOFDM system

![Graph showing Q value variation for different CD values.](image2)

**Fig. 4.8:** Variation of Q over 15, 16, and 18 ps/nm/km CD values for 64-QAM–OOFDM system
For the further analysis, effect of PMD and non-linearities has been disabled while values of GVD and chromatic dispersion parameter CD are varied. Fig.4.7 represents Q value variation with distance over varying CD using electric scope for 16-QAM-OOFDM system, fig.4.8 represents 64-QAM-OOFDM system and fig. 4.9 represents 256-QAM-OOFDM system.

A rise in CD value from 15 ps/nm/km, 16 ps/nm/km to 18 ps/nm/km results Q factor to fall from 3 dB, 2.7 dB to 2.1 dB at 150 km for 64-QAM-OOFDM system and 2.9 dB, 2.1 dB to 1.9 dB at 150 km for 256-QAM-OOFDM system. The reason for this occurrence can be attributed to the fact that different spectral components travel at different velocities leading to GVD, which results in reduction in Q factor and rise in BER.

A rise in CD value from 15 ps/nm/km, 16 ps/nm/km to 18 ps/nm/km results GVD to -19.12818 ps²/km, -20.40717 ps²/km, -22.95381 ps²/km for 16-QAM-OOFDM system. Degradation of Q factor from 8.5 dB, 7 dB to 5.8 dB reflects corresponding rise in BER to $4.146 \times 10^{-6}$, $3.067 \times 10^{-6}$ and $2.307 \times 10^{-5}$ values at 150 km. There is decrease in Q factor with higher modulation index, which occurs because higher modulation order is less energy efficient. Table 4.4 summarizes...
measurement of distortion over varying CD, GVD values in terms of Q and BER values for 16-QAM-OOFDM, 64-QAM-OOFDM and 25-QAM-OOFDM system.

<table>
<thead>
<tr>
<th>CD value (ps/nm/km)</th>
<th>GVD (ps²/km)</th>
<th>Modulation order (M)</th>
<th>Q value (dB)</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>-19.12818</td>
<td>16-QAM</td>
<td>8.5</td>
<td>4.1646e^-06</td>
</tr>
<tr>
<td>16</td>
<td>-20.40717</td>
<td>16-QAM</td>
<td>7</td>
<td>3.0647e^-06</td>
</tr>
<tr>
<td>18</td>
<td>-22.95381</td>
<td>16-QAM</td>
<td>5.8</td>
<td>2.3017e^-06</td>
</tr>
<tr>
<td>15</td>
<td>-19.12818</td>
<td>64-QAM</td>
<td>3</td>
<td>9.3645e^-03</td>
</tr>
<tr>
<td>16</td>
<td>-20.40717</td>
<td>64-QAM</td>
<td>2.1</td>
<td>2.5671e^-02</td>
</tr>
<tr>
<td>18</td>
<td>-22.95381</td>
<td>64-QAM</td>
<td>1.9</td>
<td>5.5482e^-02</td>
</tr>
<tr>
<td>15</td>
<td>-19.12818</td>
<td>256-QAM</td>
<td>2.9</td>
<td>1.3452e^-02</td>
</tr>
<tr>
<td>16</td>
<td>-20.40717</td>
<td>256-QAM</td>
<td>2.1</td>
<td>3.9872e^-02</td>
</tr>
<tr>
<td>18</td>
<td>-22.95381</td>
<td>256-QAM</td>
<td>1.9</td>
<td>5.8768e^-02</td>
</tr>
</tbody>
</table>

From these observations, it can be inferred that there is degradation in performance measured in terms Q factor and BER that increases with distance. It becomes very important to compensate the residual dispersion mismatch. One focus of this research is to compensate the effects of these impairments for performance improvement and is investigated in subsequent chapters. OFDM systems can compensate the effects of distortions like CD, PMD, and GVD by making the size of cyclic prefix of sufficient duration. This analysis on CP lengths for performance improvement is carried over in subsequent chapters.

Propagation of the pulse through fiber causes temporal change in its waveform to rectangular profile due to dispersion effects [129]. This occurs due to broadening of pulse that results dislocation of pulse position causing timing jitter. The performance is degraded due to error produced because of mis-timing between the transmissions. Mis-timing produces phase variations resulting in errors [234, 238]. So it becomes very important to measure timing behaviour as timing jitter reduces phase margin. Phase margin gives the measure of maximum phase variations that can occur to maintain the performance at certain level. This performance is usually measured in terms of BER. Phase margin is reported as range of sampling instant when BER is below than threshold BER [235].
In current chapter simulation are performed without compensating impairments (these impairments are compensated in subsequent chapters) consequently small BER are not achieved. In the subsequent discussion Phase margin measurements are reported taking $10^{-3}$ as reference BER. BER Vs sampling instant is plotted using Optsim.

![Fig. 4.10 BER Vs sampling instant for 16-QAM, 64-QAM, 256-QAM OOFDM system at 150 km.](image)

Fig. 4.10 represents BER Vs sampling instant for 16-QAM-OOFDM, 64-QAM-OOFDM and 256-QAM-OOFDM using optical link of 150 km. Phase margin is reported to be 24ps, 15ps and 6ps for 16-QAM-OOFDM, 64-QAM-OOFDM and 256-QAM-OOFDM system at 150 km. Further, fig. 4.11 represents BER Vs sampling instant for 16-QAM-OOFDM, 64-QAM-OOFDM and 256-QAM-OOFDM system using optical link of 250 km. Phase margin is reported to be

![Fig.4.11: BER Vs sampling instant for 16 QAM, 64 QAM, 256 QAM OOFDM system at 250 km.](image)
22ps, 12ps and 5ps for 16-QAM-OOFDM, 64-QAM-OOFDM and 256-QAM-OOFDM system at 250 km. Table 4.5 summarizes phase margin with respect to distance over varying M-ary QAM-OOFDM system.

An increase in transmission distance from 150 km to 250 km results fall in phase margin. This can be attributed to fact that an increase in transmission distance results BER to increase that as effect reduces phase margin. Phase margin reduction is about 3ps for 64-QAM-OOFDM and 2ps for 16-QAM-OOFDM. Higher modulation order reduces phase margin for same transmission distance. This can be attributed from the fact that higher modulation orders are more prone to errors compared to lower modulation order.

Table 4.5: Phase margin Vs distance over 16, 64, 256 QAM

<table>
<thead>
<tr>
<th>Distance(km)</th>
<th>16-QAM</th>
<th>64-QAM</th>
<th>256-QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>24ps</td>
<td>15ps</td>
<td>6ps</td>
</tr>
<tr>
<td>250</td>
<td>22ps</td>
<td>12ps</td>
<td>5ps</td>
</tr>
</tbody>
</table>

Further in order to report electrical SNR and corresponding BER the electrical signal after optical to electrical conversion is reverted to OFDM receiver MATLAB subroutine using electrical recorder. After performing OFDM demodulation and de-mapping, BER is evaluated. Fig. 4.12(a), (b), (c) represents plot representing BER Vs SNR for 16-QAM-OOFDM, 64-QAM-OOFDM, and 256-QAM-OOFDM systems. In order to compare results with theoretical expectations analytical expression eq. 4.23 is used to plot theoretical expectations.

![Fig. 4.12(a): BER Vs SNR for 16-QAM-OOFDM system](image-url)
4.12(a), (b), (c) represents BER Vs SNR performance of OOFDM system over varying M-QAM where the impairments (dispersion and non-linearities) are not yet compensated.

There is degradation in BER performance with increase in M from 16, 64 to 256. This can be attributed to the fact that lower order modulation techniques like 16-QAM are energy efficient techniques which reduces BER but decreases spectral efficiency whereas higher order modulation such as 64-QAM, 256-QAM increase spectral efficiency but result in higher BER. The BER achieved as represented by fig. 4.10 is very high. This occurs due to degradation effects produced by various
channel impairments. They are hardly reaching below $10^{-3}$. In order to achieve target performance below $10^{-9}$, the effects of these impairments need to be compensated. The compensation of these impairments for performance improvement is dealt in subsequent chapters.