THESIS FOR THE DEGREE OF MASTER OF SCIENCE IN COMMUNICATION ENGINEERING

Electronic Distortion Compensation in Optical Differentially Modulated Systems

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Abstract

A rapid research and development has been going on in the telecom industry since a few decades, which increases the demand of high data rate transmission systems. This increasing demand of growing data markets, forced the optical industry to find out new ways to improve the optical system capacity.

The capacity of an optical system can be enhanced by applying two techniques, first by increasing the bandwidth of transmission system and secondly by increasing the modulation levels of the transmission system. Due to the fiber channel impairments such as chromatic dispersion (CD) and polarization model dispersion (PMD), the OOK modulation format was capable of transmission rates up to 10 Gbps. The second possible solution to increase the transmission rate in presence of channel impairments was the multilevel modulation formats. As a result of these efforts many modulation formats such as m-QAM, m-QPSK and m-DPSK were reported for optical fiber systems.

In optical fiber channels the CD and PMD are the causes of the optical pulse broadening which put the limitation on transmission distance and spectral efficiency of multilevel modulation formats. For coherent and non coherent optical systems dispersion effects are very critical for the system performance. To solve the performance degradation due to CD and PMD, different types of compensation techniques were introduced for coherent and non-coherent direct detection systems. Due to these compensation techniques the transmission distance of optical systems can be enhanced many times.

The aim of this thesis work is to observe and mitigate the CD effects on non-coherent direct detection differentially phase modulated DPSK and DQPSK systems. The non coherent differential phase modulated systems modulate the information on differential phase. In the m-DPSK receiver, the optical signal passes through an optical delay line interferometer and a balanced detector. During the process of the detection the phase field information lost. It is however possible to recover the received phase field information in the electrical domain by digital signal processing (DSP). By using DSP and exploiting the orthogonal fields of non coherent direct detection DPSK receivers, the complex optical received field can be reconstructed in the electrical domain. It is then possible that the reconstructed field can be compensated by the electronic dispersion compensation (EDC) method. In EDC, numeric compensation or the inverse CD transfer function is used for compensation. After mathematical modeling and simulation, and by evaluating the obtained results, we demonstrated that in non coherent differentially phase modulated DPSK and DQPSK systems received optical field can be reconstructed in the electrical domain by DSP and reconstructed optical signal can be compensated by such numerical compensation techniques.

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Abbreviation Used in Text

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CD	Chromatic Dispersion
DCF	Dispersion Compensation Fiber
DQPSK	Differential Quardrature Phase Shift Keying
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
EDC	Electronic Dispersion Compensation
EDFA	Erbium-Doped Fiber Amplifier
GVD	Group Velocity Dispersion
NLSE	Non-Linear Schrödinger Equation
OOK	On-Off Keying
PMD	Polarization Mode Dispersion
PSK	Phase Shift Keying
QAM	Quardrature Amplitude Modulation
QPSK	Quardrature Phase Shift Keying
SPM	Self Phase Modulation
WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing

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Chapter 1

Introduction

In older times humans invented different methods for long and short distance communication. They were used to send the desired information from one location to another location by using different communication methods and light was also one of the more reliable methods of the communication. But there was no any scientific method, which could use the light as signal in communication system. First time in 1880 the Alexander Graham Bell invented the Photo Phone and did some experiments to transmit the light as a signal. He successfully used the sun light as signal in his experiment of light signal communication (1) [1]. In the 19^{th} century light was introduced as a mean of proper optical communication systems but optical communication did not become popular until the invention of different light wave communication devices. These devices were light generating sources, like lasers, light guiding medium, known as the optical fiber and light detecting photo detectors. In the 1960's a Dutch scientist Abraham Val Hell made the first clad fiber, which was capable of maintaining total internal reflection, having the losses of 1000 db/km. [2] In 1962 an American scientist R. N. Hall invented the first semiconductor laser diode which was capable of radiating the coherent light emission at 850 nm wavelength from GaAs (Gallium Arsenide) junction [3].

Over the time, research and development gradually increased in the optical field, fiber losses were reported to reduced below the 20 db/m, and soon Bell laboratories developed a fiber having loss of 4db/Km [3]. Mean while some new semiconductor lasers were reported, they were capable of efficient and continuous working at room temperature. The availability of optical devices encouraged the optical industry to develop the commercial optical communication system. In 1977 an American company "General Telephone and Electronics", deployed their first optical communication system on trial basis, which was capable of carrying the data rate of 6 Mbps (2) [2]. In the early 1980's commercial optical systems were available in the market. Since 1975 to 2000 a tremendous development has been done in optical communication systems to fulfill the increasing demand of the bandwidth for the growing optical communication market. Since the deployment of optical communication system was increased multiple times every year and recently existing optical systems were approximately working on their matured capacity (3)[4].

A modern optical communication system consist of three generic parts a transmitter, a communication medium and a receiver. Every part has its own functionality and design, but system performance and requirement depend on the system model and design [4]. Transmitter consists of a driving circuit light source and optical modulator. Driving circuit is responsible to operate the optical source to generate the optical wave and optical modulator encodes the electrical information on an optical continuous wave (CW). The required pattern of the modulating signal depends upon the transmitter modulation technique. Optical systems mostly use digital modulation techniques and electrical information signals can be modulated by direct modulation of an external modulator as per transmitter design (3) [4].

The main focus of the recent years' research was to introduce and explore the new techniques and features of the optical systems, and employing them in such a way that the capacity and performance of conventional optical systems should increase. The wavelength division multiplexing was introduced and employed in transmitter design to increase the optical transmission capacity. Increasing the number of transmission channels enabled the optical system to transmit the several times more data than a convention optical system. This technique gave rise to a tremendous increase in system capacity. The dense wave division multiplexing (DWDM) systems are deployed all over the world in both long haul and short haul optical networks. Presently DWDM systems are working on their matured capacity. To increase the system capacity new optical modulation formats is under study. They need to be more robust and resilient against channel impairments and other noises. But all these benefits of multilevel modulation techniques were at the expense of system complexity and cost (3) [4].

But increasing the transmission capacity of optical communication systems also depends on the optical communication medium. Optical communication medium are generally considered as optical fiber cables. These optical fiber cables are designed and manufactured with transparent core and transparent cladding with low index of refraction. Via total internal reflection the fiber acts like a wave guide. If fiber maintains this phenomenon along its length then it generates small losses. A fiber which supports single mode of propagation is called single mode fiber (SMF) and those who support many transverse modes are called multimode fiber (MMF). At a certain wavelength every optical fiber has minimum attenuation for each fiber mode. SMF has minimum attenuation loss of 0.2 dB/Km around 1.55 µm wave length (3)[4].

In the long haul optical communication systems, after a certain distance signal power is decreased by channel impairments. To improve the signal power after certain distance, amplifiers or repeaters are used to improve the signal power. In earlier optical communication systems amplification process was in the electrical domain and signal was required to bring back in to electrical domain from optical. But after invention of the EDFA (Erbium Doped Fiber Amplifier) it became easy to amplify the degraded signal power in the optical domain. Transmitted optical pulses also broaden by linear impairments of the fiber, like chromatic dispersion (CD) and polarization mode dispersion (PMD). The dispersive pulse broadening causes inter-symbol interference (ISI) between the optical symbols. The ISI cause of severe degradation in multimode fiber (MMF) system, and due to this reason SMF is preferred to use as optical communication channel. In such a noisy transmission channel it is normally recommended to keep the transmitted pulse in its bit or symbol slot to avoid ISI because it increases the symbol detection problem at receiver. Other important phenomena that also cause signal degradation are nonlinear effect and fiber attenuation. These effects can be analyzed by the NLS (Non Linear

Schrodinger) equation. These non linear effects are significant in long haul and undersea communication systems (4). To mitigate the dispersion effects dispersion compensating fiber are used in optical domain but electronic dispersion compensation (EDC) is also an attractive alternative to mitigate the dispersion effects (5) [25].

The optical receiver is connected at the other end of the system; through the optical fiber. Generally it consists of photo detectors, amplifiers, filters and decision circuitry. The optical receivers generally use two types of detection techniques in the receivers; coherent and non-coherent. The coherent system needs a local oscillator (LO) to detect the reference frequency or phase information to extract the received symbols information correctly. Similarly non coherent system does not need the LO for the detection of reference frequency or phase. The non coherent systems use direct detection technique like On Off Keying (OOK) or self coherent direct detection systems like m-DPSK (Differential Phase Shift Keying), for the received symbols (5).

The design of the receiver depends on the required system performance. But the performance of the non coherent direct detections receiver of differentially modulated system is degraded due to CD in the channel and the loss of the received optical field information during the detection process in the receiver. It can be possible to recover the lost optical field information in electrical domain by applying the DSP. So by designing such a receiver it can be possible to use the non coherent differential phase modulated systems in DWDM systems to enhance the performance.

As we discussed above in long haul DWDM SMF systems CD and PMD are the main dispersion effects which cause pulse broadening. Generally electronic dispersion compensation (EDC) technique is used for the mitigation of chromatic dispersion. It is also possible to mitigate the chromatic dispersion effects by using the numeric or chromatic dispersion inverse transfer function as compensation technique for chromatic dispersion. A lot of research has been done and still going on to explore the electronic compensation techniques for chromatic dispersion compensation (5).

This report is comprised of 6 chapters. The first chapter is related to introduction of optical fiber systems and their major issues. In chapter 2 we discuss the modulation types, modulation formats and their transmitter design, in chapter 3 we discuss the fiber channel impairments, e.g. CD and its after effects on the signal. In chapter 4 we deal with the DQPSK transmitter and receiver design of implemented model and also discussed about the offline processing and its scope. In chapter 5 we present the results and in last chapter 6, the future work and conclusion.

Chapter 2

Optical Modulation Formats and Designs

In this chapter we will discuss the modulation techniques and types of modulation formats required for optical communication systems. A communication system contains many stages as shown in figure (1) and every stage performs a certain functionality. An optical source could be a laser or LED, which emit a continuous optical wave at a fixed wave length $(v_o = {}^{c}/_{\lambda_o})$. The selection of a fixed wavelength depend on the required carrier frequency (f_c) and it can be made from the ITU recommended long wave spectral bands (O, E , S, C, L and U), ranges from 1260 to 1675 nm, and shortwave spectral wavelengths, ranges from 770 to 960 nm band (6). Optical signals can reach the receiver in real time by using a suitable modulation technique. In modulation base band input of electrical signals are encoded on a higher optical carrier frequency to convert the baseband signal in to pass band.

A source generates the information signal in analog or discrete form, but in reality most of the signals are analog. Generally discrete signals are generated from analog signals by sampling process through the analog to digital convertor (ADC). The sampling frequency f_s depends on the inverse of sampling time$(f_s = \frac{1}{T_s})$. By the quantization process a discrete signal is converted in to bits. Binary bits have two levels +1 and -1 but discrete signals have many levels then binary. The number of bits m are required to convert the each discrete sample in to digital is $M = 2^m$.

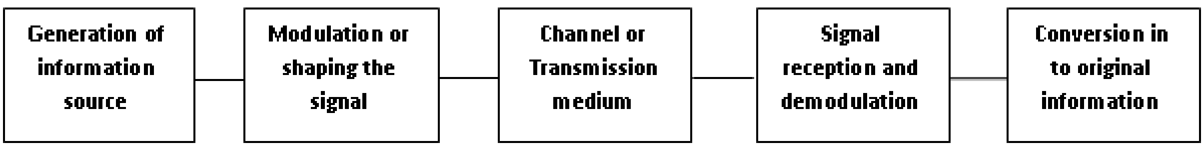


Figure 1: Communication system stages.

Information signals are generally called baseband signals. The baseband signals are used to modulate a high frequency and high power signal called the "carrier"**.** In optical systems the carrier is a continuous optical wave radiated with the speed of light by the laser at a fixed wave length. Analog and digital signal can be modulated on the carrier. The difference between digital and analog modulation is that the digital modulated signal has abrupt changes or transitions but analog modulated signal is continuous. In other words modulation is the choice of encoding the information signal on the optical carrier through signal space and this can be represented by a symbol constellation (7).

2.1 Digital Modulation

There are three main types of digital modulation where each modulation technique uses a particular parameter (frequency, phase, or amplitude) of the carrier to encode the transmitted information. Optical communication system use one parameter of the optical carrier wave (CW) for digital modulation and modulation format is chosen according to the transmitter design. In amplitude modulation the amplitude of the carrier vary with respect to information signal and in frequency shift keying FSK frequency of the sinusoid is vary with respect to information signal. Phase shift keying is simply varying the phase of the carrier with respect to information signal (8).

A digital modulated signal consists of discrete sets of any modulated wave forms$\{y_1(t), y_2(t), y_3(t), \ldots, y_M(t)\}$. These discrete sets are called alphabets of $M \geq 2$ (M=2 represent binary modulation) or communication symbols. Transmitters and receivers always use the same communication symbols to send and receive the information. Transmitter transmits the each symbol in one symbol time duration or time slot (Ts), at the rate of symbol rate $R_s = \frac{1}{T_s}$ (each symbol has $log_2 M$ bits per symbol). The bit rate is:

$$\mathrm{R}_b = \mathrm{R}_s \, log_2 M \qquad (2.1).$$

The digital modulation formats, which have at least two symbol alphabets, are called multilevel modulation formats. Modulation format can be increase by placing the more symbols in signal space by expanding the signal space dimensionality (9).

Before choosing the modulation technique many aspects of modulation formats can be considered; one aspect is the redundancy. Redundancy can be achieved in modulation by line coding or by applying the error correcting techniques like FEC (forward error correction), also called the coded modulation technique.

Redundancy is added to protect the transmitted data at the cost of extra bandwidth. If the redundancy in digital modulation formats is required then we add different coding schemes in our transmission scheme. If any coding scheme which used to prevent the transmitted symbols then we call it line coding scheme.

2.1 Modulator Types

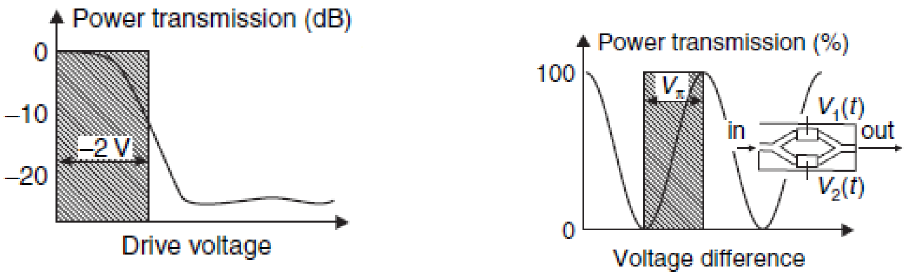
There are three types of optical modulators for the input electrical signal modulation.

Direct Modulator (Directly Modulated Lasers)

Direct modulation lasers are the most commonly used method in optical modulation which use to modulate the electrical signal on the optical carrier. The electrical current is directly modulated to laser current and the laser generates a modulated optical signal called intensity modulated or on off keying (OOK) modulation format. The OOK modulation format is common in use for modulating the electrical signal up to 10 Gbps. Above this data rate external modulators are preferred because of the laser chirping phenomenon at higher data rates. The chirping phenomenon broadens the optical spectrum and increases the distortion for optical pulses. In optical fiber channels such optical pulses are further broadened by the channel dispersion (9).

Electro Absorption Modulator

Externally absorption modulators have a pin semiconductor structure. They are used to control the laser beam intensity with the voltage as shown in fig. 2a.



Electro Absorption Modulator (a)

MZM Modulator (b)

***Figure 2:** Transmission function of the EAM (a) Power transmission function of MZM (b) [7].*

They operate on low voltages and have high speed operation, and are capable of modulating data up to 40 Gbps. But they have the same problem of chirping for higher data rates as direct modulation (9).

MZM Modulator

The Mach-Zender Modulator is the most common external modulators. The light source emits constant amplitude of light and it split in to two paths by 3 dB coupler as shown in the figure (2-b). Both the arms of the coupler work as a phase modulator and input voltages V_1 and V_2 applied to the both arms of phase modulator to change the phase of optical carrier. At the end of coupler these light signal combined with a constructive or destructive mode (3).

The transfer function of the MZM as 3dB coupler,

$$\begin{bmatrix} A_b \\ A_c \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} * \begin{bmatrix} 1e^{i\emptyset_1} & 0 \\ 0 & e^{i\emptyset_2} \end{bmatrix} * \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} * \begin{bmatrix} A_i \\ 0 \end{bmatrix} \qquad (2.3)$$

A_i, is the incident optical field and $\emptyset_j(t) = \frac{\pi V_{j(t)}}{V_\pi}$ is the phase shift in j arm when $V_j\ (j = 1{,}2)$ voltage applied across the modulator arm ($V_\pi = Voltage\ required\ to\ bring\ a\ change\ of\ \pi\ phase\ shift$). Then modulator response or transmissivity would be

$$t_m = \frac{A_b}{A_i} = \cos\left[\frac{(\emptyset_1 - \emptyset_2)}{2}\right] exp^{\left[\frac{(\emptyset_1 - \emptyset_2 + \pi)}{2}\right]} \qquad (2.4).$$

To avoid the chirping problem and to create the constant phase shift, the same amount of voltage but in opposite polarity is applied in both arms by keeping the biasing voltage $V_2 = -V_1\ (t) + V_b$ constant. This type of MZM operation is called push pull operation. MZM are used for high data rate modulation and used in long haul communication preferably (3).

2.2 Pulse Shaping

The pulse shaping technique is used for representing the information bits in to suitable electrical or optical form, during the transmission. The most basic and theoretical pulse shape is the square pulse but practically it is not possible to generate such a pulse with sharp edges as shown in figure (3). Due to the sharp edges of the square pulse, it has an infinite spectrum which cause of taking wide bandwidth. The band width of the pulse can be reduced by rounding the edges of the pulse or by increasing the pulse time duration (10). Only for the purpose of simulation and theoretical understanding we use square pulses.

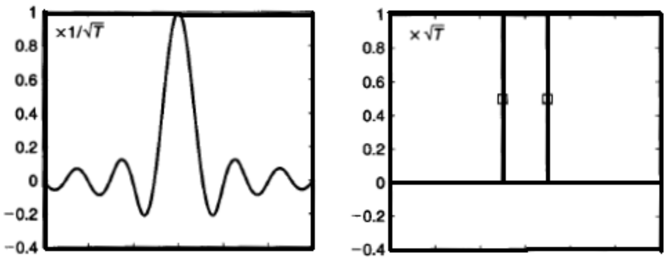


Figure 3:- Square pulse replica is sinc pulse in frequency domain having large BW (19)

An improved version of the square pulse is the raised cosine (RC) pulse which is normally generated by adding the extra roll off factor In the time domain the RC pulse can be written as

$$V(t) = \frac{\sin\left(\frac{\pi t}{T}\right)}{\pi t/T} * \frac{\cos\left(\frac{\alpha\pi t}{T}\right)}{1-4\alpha^2 t^2/T} \qquad (2.5).$$

Here α is a roll off factor of the pulse and the extra bandwidth of the pulse $\frac{1+\alpha}{2T}$ as shown in fig. 4.

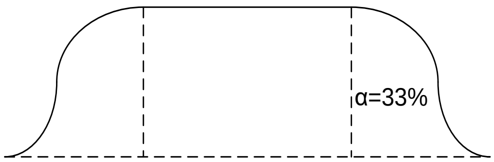


Figure 4:- RC pulse with 33% roll factor the dashed lines are showing the actual pulse (19)

Generally only some 30% extra band width is used of the total pulse band width [12].

RRC (root raised cosine) pulse is also used for communication but it follows the orthogonal criteria.

$$\sum_{n=\propto}^{\propto} \left|V\left(f-\frac{n}{T}\right)\right|^2 = K_0 \qquad (2.6).$$

Here $V(f)$ is the Fourier transform of $V(t)$ and K_0 is a real constant. The RRC pulse has symmetric shapes in time domain and it is the square root of the RC (raised cosine) pulse (11).

These pulses are used to map the symbols information on the pulses to form a pulse train. One pulse normally represents one symbol and mathematically we can represent it as

$$S(t) = \sum_{n=0}^{N} a_n V(t - nT_s) \quad (2.7).$$

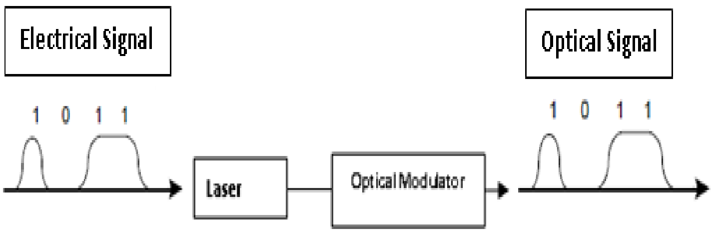
Where $a_0, a_{01}, a_{02}, \dots a_n$ are the information symbols mapped on the pulse shape V_t to generate a modulated pulse train. This type of pulse train $S(t)$ is generated at the modulation rate and used in many advanced modulation formats (8) (7)

2.3 Optical Modulation Formats

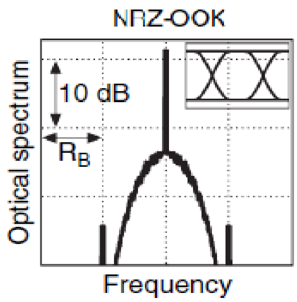
The different types of modulations formats used in optical fiber communication are discussed below.

2.4.1 Non Return to Zero (NRZ) OOK Modulation

This is the simplest modulation format in optical communication systems used for intensity modulated direct detection systems (IM/DD). It requires less bandwidth then the RZ format. The power level of the pulses does not change or remain same for consecutive 1's bits. NRZ OOK pulses can be generated by a directly modulated laser or an electro absorption modulator. Many existing optical communication networks are using directly modulated schemes as shown in figure 5.



(a)



(b)

Figure 5:- Input NRZ Electrical signals and output same replica in Optical NRZ Signal (a).Optical spectrum of NRZ OOK is shown. Spectrum is continuous spectrum with strong discrete tone at peak. It shows a strong tone at carrier wave length (b) (8)

These pulses can also be generated by the external MZM modulator to get a chirp free NRZ. OOK pulses NRZ OOK has good frequency spectrum as shown in figure (5-b). It is resilient against dispersion to some extent but it can't be fully resilient against chromatic dispersion and non-linearities [7].

2.4 Return to Zero modulation Format

RZ modulation format can be used in cases where the pulse shape is fully contained in each symbol time duration. It is used in OOK, DPSK and DQPSK

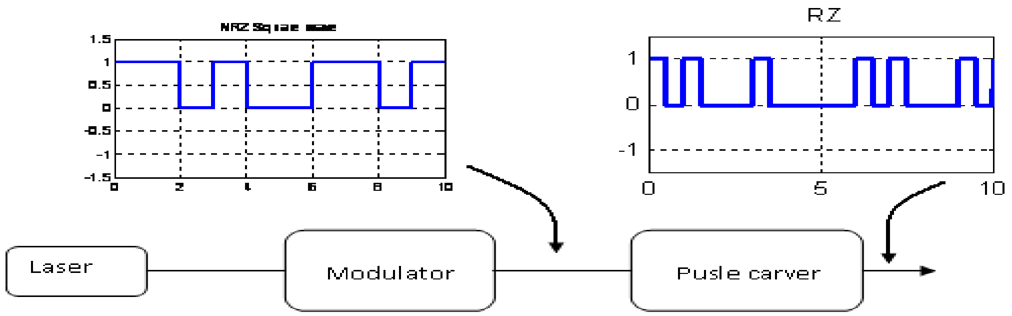


Figure 6:-Dual Driver Modulator with Pulse Carver used to generate RZDQPSK Pulses

There are many methods to generate the RZ pulse format. A simple method to generate the RZ pulse format is by employing a lasers and a modulator as shown in figure (4)(6). The laser generate a uniform time interval continuous pulse train and modulator encode the electrical input signal on optical CW in such a way that for bit "1" signal present in the output wave form and for zero no output in the wave form.

Another way of generating the RZ wave form is first to generate an NRZ wave form and then convert

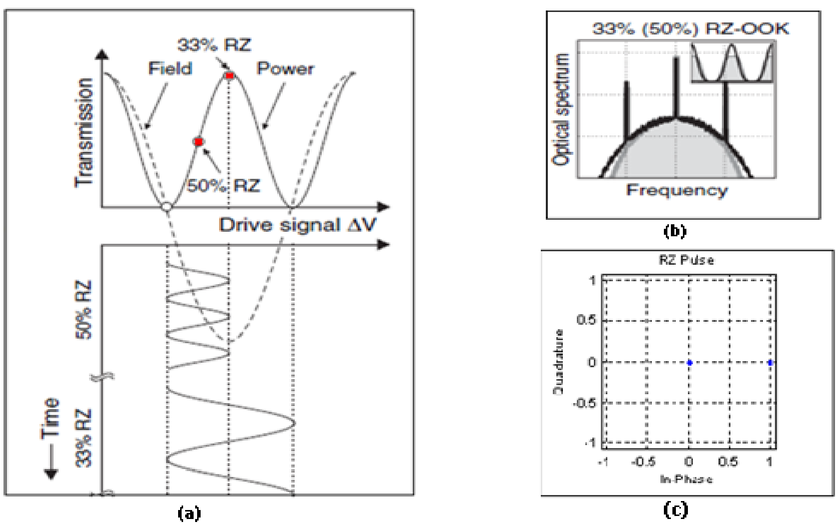


Figure 7:- MZM is used as Pulse Carver at 33% and 50% duty cycle and its basing voltage points are shown in circle (a) (8)Frequency spectrum is shown of RZ OK pulse showing a broader spectrum (b) (8) Symbol diagram for RZ OOK is shown (c).

the generated NRZ wave form in to RZ with the help of a second modulator known as a pulse carver. Pulse carver mostly operates on the half of the minimum and maximum of the MZM driving voltages and result in a full maximum and half maxim pulse generation for half of bit duration as shown in figure (7-a) [4]. An issue of synchronization occurs when two MZM (Modulator and Pulse carver) are used the configuration as in figure (6). To overcome the synchronization issue a simple configuration of a single modulator and NRZ electrical input signal can be used for the generation of the RZ format (4).

The MZM biasing voltage V_b and the input voltage V_1 can be set to the desired duty cycle RZ pulse by using the transfer function of the modulator (3),

$$power\ tranfer\ function\ of\ MZM = cos^2\left(\frac{\pi}{2V_\pi}[2V_1(t) - V_b]\right) \qquad (2.8).$$

An important feature of the RZ format is that it requires 2.3 dB less OSNR then NRZ format for a given BER for a same optical system design. The RZ format require more bandwidth then NRZ and its spectrum is also more broadened then NRZ, which cause to stimulate the non linear effects at high data rates during the transmission more than the NRZ format (8).

2.4.2 *Binary Differential Phase shift Keying*

When a complex wave form is multiplied with a complex number which lie on a unit circle then this type of modulation is called phase shift keying (PSK) modulation. Optical communication may use PSK modulation but due to the square law of a direct detection receiver, the received optical phase information is lost. Coherent receivers use an optical local oscillator (OLO) to overcome this problem.

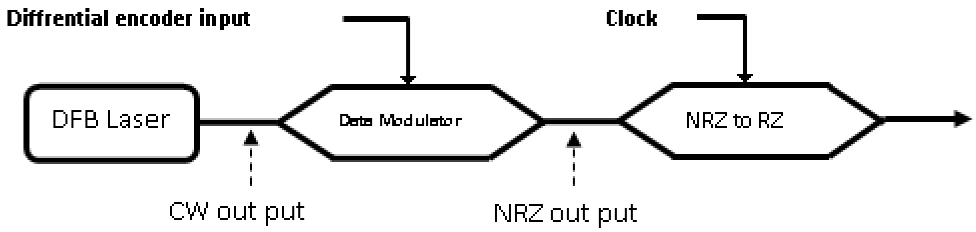


Figure 8:-DPSK receiver configuration with double MZM's

Another way to overcome this problem is to use differential phase shift keying (DPSK) for non coherent optical communication systems. In the DPSK format the optical modulator encodes the differential phase of two adjacent bits of the electrical signal on the optical CW. If the electrical information bit is 1 optical modulator encode the differential phase information by π phase shift on optical pulse and if the bit is 0 then phase would be zero and pulse phase will not change (8)[12].

A DPSK transmitter with a double MZM configuration is shown in figure (8). An electrical differential encoder output is the input to first MZM to generate the differential NRZ optical signal. The output of the NRZ optical signal is the input to 2nd modulator, called NRZ to RZ convertor which finally generates the RZ DPSK signal. To generate the NRZ signal the MZM biasing voltage set at half of theV_b, ($V_b = V_\pi/2$) but for RZ pulse generation from NRZ pulse, the biasing voltage for the same type of MZM is set at its peak voltage $(V_b = V_\pi)$. The transfer function of the first modulator,

$$\mathrm{Tm}(\mathrm{V1}) = \sin^2\left(\frac{\pi}{2V_\pi}[2V1(t) - V_\pi]\right) = cos^2[\pi V1(t)/V_\pi] \qquad (2.9).$$

Where, Tm is the transmissivity or power transfer function of the MZM (3).

Another design of a DPSK modulator is shown in figure (9). It consists of a single phase modulator and a delay line interferometer (ODI) to generate the DPSK modulated signal. In this configuration electrical signals are already in differentially coded NRZ bit stream which drive the phase modulator. When the input bit is 1, the Phase modulator encodes the π phase on optical pulse.

The output of the phase modulator is fed to delay line interferometer, and the optical field split by 3dB

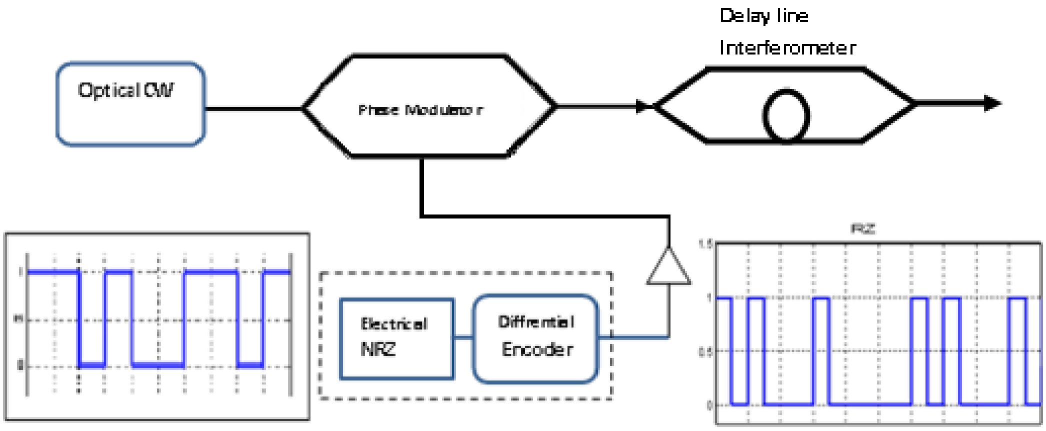


Figure 9:-Block diagram of DPSK transmitter generating RZ format

coupler and pass through both coupler arms. One coupler arm produces one bit delayed optical field (*path length equal to one bit time duration*) and the second arm passes the optical input signal without delay, and both arm output recombine in constructive and destructive mode at the coupler end, and to the RZ DPSK signal.

The Differential pre-coder (or encoder) is shown in figure (10). Its working principal is a modulo 2 adder operation. It consist of a logic Ex-OR operation as shown in figure (10) below,

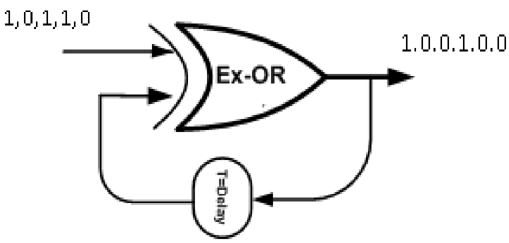


Figure 10:-A DPSK pre-coder

The purpose of the pre-coder is to generate the differential phase information and encode this information on the optical CW.

The transmitted optical signal is then $X(t) = \sum_n an\, p(t - nMTb)$,

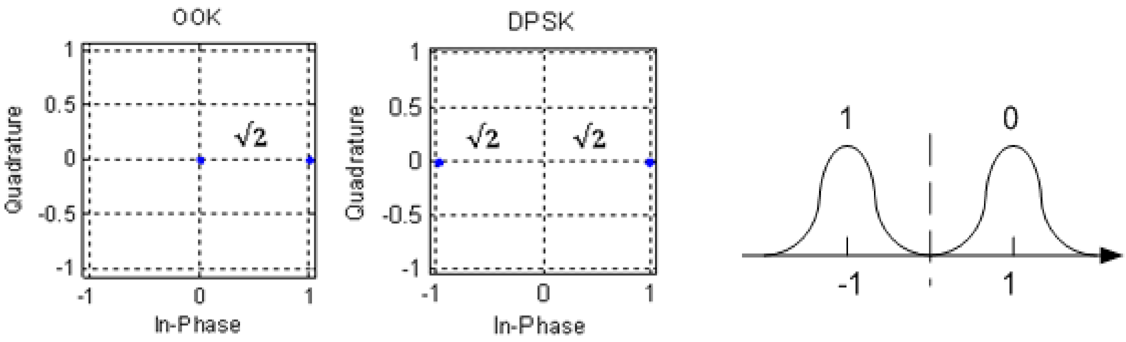
where the pulse shape $p(t)$ could be RZ or NRZ e.g.

$$p(t) = \left\{ \sqrt{\frac{E_b}{T_b}} \right\} \qquad \text{(2.10)For NRZ DPSK.}$$

$$p(t) = \left\{ \sqrt{\frac{2E_b}{T_b}} \cos(\frac{\pi}{2} cos^2(\frac{\pi t}{MTb})) \right\} \qquad \text{(2.11)For RZ DPSK.}$$

Here E_b is the bit energy in one bit unit time (T_b) and pulse shape $p(t)$ exist in bit time interval(8).

To compare the performance of the DPSK and OOK signal, DPSK signal is better than the OOK signal.



(a) *(b)*

Figure 11:- Scatter plots of DPSK and OOK signal (a) Transmitted DPSK pulses for 0 and 1 bit (b).

The receiver sensitivity is improved by 3dB over OOK as shown in figure (11). We can see that DPSK signal spaces are at double distance of OOK. If the distance between the signal spaces increased, then the impact of noise and dispersion on received signal would be less. Because increasing the distance between signals space enhance the robustness of the DPSK signal against noise and OSNR by 3dB over OOK. The transmitted power for OOK and DPSK modulated signals in the presence of non linear effects at 10Gbs would be same. Similarly the performance of two systems having different distance lengths for the same BER would be different. If DPSK system is compared for the same design and distance then DPSK has better performance than other system due to its SNR robustness(8).

2.4.3 *Differential Quadrature Phase Shift Keying (DQPSK)*

In present optical communication systems DQPSK modulation format gains a lot of attention. DQPSK is the prominent and effective modulation format in optical communication. It's the true multilevel modulation format having four different phases which are used to transmit the desired information (9).

The DQPSK transmitter use the same approach to generate DQPSK modulation formats as the DPSK transmitter does. DQPSK transmitter uses the nested MZM configuration as shown in the figure (12). The set of two MZM's are shown in figure (13), perform function of phase modulators. The MZM exploit the phase of optical CW by applying the certain level of phase modulating voltages ($V1, V2, V3$) and generate the required phase difference in coupler branches. The field transfer function of V_1 and V_2 of the MZM is:

$$TE\ (V_1, V_2) = \frac{1}{2}\left\{e^{j\phi(V_1)} + e^{j\phi(V_2)+j\psi}\right\} \quad (2.15)$$

$$= e^{j\phi(V_1)+j\phi(V_2)/2} cos\left[\left(\phi(V_1) - \phi(V_2)\right)/2 - {}^{\psi}/_{2}\right] \quad (2.16)$$

Here ψ is the additional phase shift in a coupler branch for modulator biasing (7).

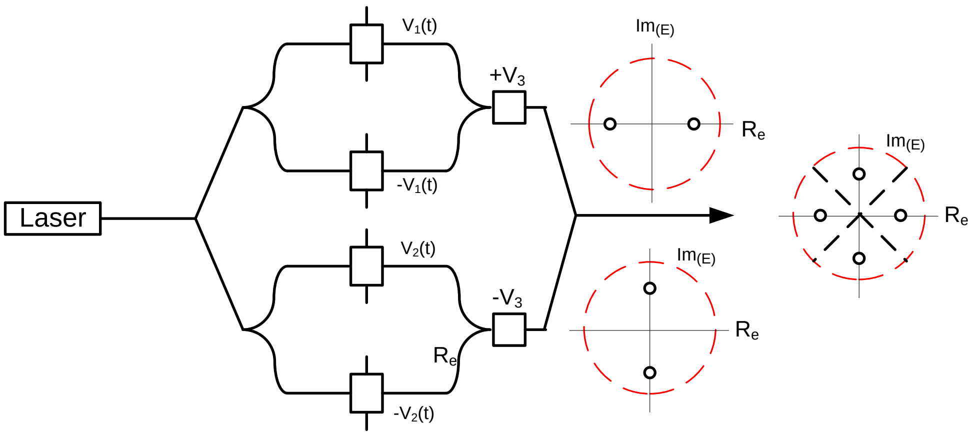


Figure 12:-The structure of a nested MZM with Phase quadrature modulator.

For quadrature modulation, it is preferred to use the double nested MZM modulators. In each MZM arms two independent bit streams (I bit and Q bit) are modulated on the optical CW. By using the MZM's in push pull configuration $(+, -V1)$, $(+, -V2)$ the chirping problem can be avoided. The third MZM is use to create the phase difference of 90 degree between the outputs of two MZM's. Using this configuration each MZM can generate the exact π phase shifts. This type of configuration can be drive by binary electronic drive signals. This configuration generates the NRZ–DQPSK signals but if the output signal fed to a pulse carver then RZ–DQPSK signals can be generated (9).

Dual drive MZM can be used to generate the NRZ DQPSK signal and by adding one phase modulator for pulse carrying we can generate the RZDQPSK modulation format.

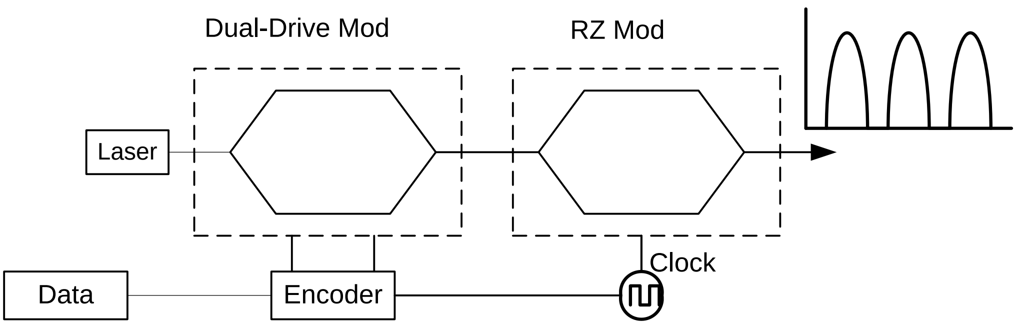


Figure 13: DQPSK RZ Modulator based on the out of DQPSK NRZ modulator

The design of the DQPSK transmitter is shown in figure (13). A clock is required to synchronize both the dual drive modulator and RZ modulator.

Chapter 3

Fiber Channel Impairments and Chromatic Dispersion

In optical communication systems the optical signal propagates through the optical fiber channel and during this transmission it becomes distorted. The signal degradation phenomenon occurs during the transmission due to different linear and non linear effects. It then becomes necessary to control and compensates these linear and non linear degradations to get a better signal at the receiver.

2.5 Light-wave Propagation in Fiber Channel

The basic propagation equation in optical fiber channel for optical bit steam in electrical form can be written as [4]

$$E(r,t) = R_e[\hat{e}F(x,y)A(Z,T)\exp(i\beta_{oz} - i\omega_o t)] \quad . \qquad (3.1).$$

In this equation the parameters that can vary during propagation along the fiber are the distance z, $\hat{e}$ is polarization vector and $\boldsymbol{A(Z,T)}$ complex amplitude of the envelope. The polarization vector $\hat{\mathbf{e}}$ changes due to fiber birefringence effects, only complex amplitude $A(Z,T)$, changes with distance Z. The propagation constant β_o depends on the carrier frequency ω_o. In spectral domain we can write the complex input optical signal at Z=0,

$$A(0,\omega) = A(0,\omega)\exp^{i\beta_o z} \qquad (3.2).$$

In single mode fibers each spectral component propagate at different propagation constant $\beta_p(w)$ which can be written as

$$\beta_p(w) = \beta_L(\omega) + \beta_{NL}(\omega_o) + i\alpha\frac{(\omega_o)}{2} \quad . \qquad (3.3).$$

Here, $\beta_L(\omega)$ is the linear part and equivalent to $\bar{n}(\omega)\frac{\omega}{c}$ and frequency ω depend on the mode index $\bar{n}$, the dependence on mode index becomes the cause of pulse broadening. The α is fiber attenuation constant, responsible for the fiber losses. The non linear effects β_{NL} have very low impact on signal power but it counts in long haul DWDM systems. Expanding the linear effectsβ_L around the carrier frequency $\Delta\omega$

$$\beta_L\,(\omega) = \beta_1(\Delta\omega) + \frac{\beta_2}{2}\,(\Delta\omega)^2 + \frac{\beta_2}{2}\,(\Delta\omega)^2 \qquad (3.4).$$

Where $\beta_1 = \frac{1}{V_g}$, produce a group delay $(\tau_g = z/V_g)$ which leads to polarization modal dispersion (PMD) [4].

$$\Delta\tau_{Pol} = Z\left|\beta_{1x} - \beta_{1y}\right| \qquad (3.5).$$

β_2 factor cause of spreading the group velocities of the wave because the group velocities depend on the wave frequency. This spread of group velocity is known as group velocity dispersion or chromatic dispersion. β_2 is also a major component of dispersion in SMF and defined as

$$D = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) \qquad \text{or } -\frac{2\pi c}{\lambda^2}\,\beta_2 \text{ (ps/Km-nm)} \qquad (3.6).$$

β_3 is considered as third order dispersion parameter. This factor is related to dispersion and dispersion slope (3).

2.6 Dispersion Theory and Concept

As we already mentioned the degradation of transmitted signal in the fiber are generally classified as intermodal dispersion, intramodal dispersion, polarization mode dispersion and higher order dispersion effects. All these dispersion effects can be explained and understood by understanding the group velocity phenomenon.

2.7 Intermodal Dispersion

Intermodal dispersion is the dispersion phenomenon, which occurs, only in multimode fibers. In multimode fibers many modes are transmitted and each mode has different group velocity but at the same single frequency (5).

2.8 Intramodal Dispersion or Chromatic Dispersion

In single mode fiber due to the finite spectral emission of optical source pulse spreading occur. From equation (3.6), group velocity is dependent on the wave length and due to this dependency on λ the spectral width increase the dispersion. Spectral width is the band or group of wave lengths over which an optical source radiate the light wave. The source emits the most of the light in this range. For example, LED has much broader spectral width than a laser. There are two main causes of intramodal dispersion (5) which will be discussed below.

3.4.1 Material Dispersion

Material Dispersion is generated by the dispersive medium. The refractive index of a core varies as a function of wave length and group velocity (V_g) of a mode is also a function of the refractive index so the spectral components of a mode will propagate on different speeds with respect to the wave lengths. This dependency on the wave length cause of the pulse broadening. The dispersion D varies at a certain wave length as shown in the equation (3.5). At a certain wave length dispersion vanish and that wave length is called zero dispersion wave length (λ_{ZD}). Near this *wave* length dispersion behave linearly where D would be

$$D = s(\lambda - \lambda_{ZD}) \qquad (3.7).$$

Where S is the slope and depend on

$$S = (2\pi c/\lambda^2)^2 \beta_3 \quad (3.8).$$

Dispersion (D), zero dispersion wavelength (λ_{ZD}) and slope parameters (S) are specific to the fiber. Every fiber has different values for these parameters. (3),

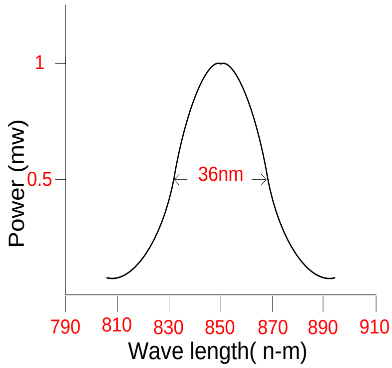


Figure 14: Wave length at 850 nm, pulse spectral width at half power is 36nm. Pulse is also more confined around 850 nm peak wavelengths.[15]

3.4.2 *Waveguide Dispersion*

Waveguide Dispersion occurred when an optical pulse travel in an inhomogeneous medium and pulse don't remain confine properly in to the core. In other words the central part of the pulse is more confined or the portion of the transmitted pulse which has more power would be more confined and travel along the fiber as shown in figure (14). This type of dispersion occurred due to refraction of light, in the cladding because cladding has lower refractive index then core. Light traveled faster in the cladding then the core. Waveguide dispersion also depend on the propagation it can't not be ignored in single mode fibers (5).

2.9 *Polarization Modal Dispersion*

Polarization dispersion also causes pulse spreading. When an optical signal travels through the fiber, and the fiber material does not have uniformity along the fiber length then refractive index of polarization states become changed, and each mode travel with a different velocity. This difference in propagation time causes the pulse spreading. The difference is between the two polarization state is mention in equation (3.5) (5).

In general we conclude that the dispersion is a time domain spreading or broadening of the optical pulses when they travel through the fiber. The effective refractive index (A_{eff}) of the fiber depend on the transmitted carrier frequencyω. A pulse is composed of many frequency components and each component is dependent of its certain group velocity, when these spectral components travel in the fiber they travel with little different speeds with each others. This phenomenon is called as group velocity dispersion (GVD). Different group velocities of the spectral components are cause to delay the arrival between the spectral components at receiver end. The delay in arrival of pulse spectral components is called differential delay.

2.10 Impact of Dispersion on Optical Pulses

The differential delay increases along the distance and it has more significant impact on long haul transmission. It degrades the signal quality and increase the bit error rate which decreases the system OSNR.

Writing the linear part (4.3) in the time domain to observe the dispersion we obtain:

$$\frac{\partial A}{\partial z}+\beta_1\frac{\partial A}{\partial t}+\frac{i\beta_2}{2}\frac{i\beta_2}{\partial t^2}+\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=i\beta_{NL}A-\frac{\alpha}{2}A \qquad (3.9).$$

Equation (3.9) is the basic propagation equation for single mode fibers. Here $i\beta_{NL}A$ is a non linear part of the equation and can be rewritten with normalized amplitude as $\beta_{NL}=\gamma|A|^2$, where $\gamma=\frac{2\pi n_2}{\lambda_0 A_{eff}}$ represent the non linear effects in the fiber. When the β_2 is not close to zero we can skip the β_3 and $\beta_1$the equation would be

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{i\beta_2}{\partial t^2}=i\gamma|A|^2A-\frac{\alpha}{2}A \qquad (3.10).$$

This equation is called non linear Schrödinger (NLS) equation and it can be used to analyze three kinds of degradation in the fiber by their respective parameterβ,α,γ. In this thesis work we were more focused on the study of linear degradation β_2 (chromatic dispersion) impact (3).

As we have discussed earlier group velocity dispersion (GVD) causes the optical pulse degradation which leads to pulse broadening when it is received at receiver. To simplify the Schrödinger equation for chromatic dispersion we set $\alpha=0$ and $\gamma=0$ and obtain

$$\frac{\partial A}{\partial Z}+\frac{i\beta_2}{2}\frac{i\beta_2}{\partial t^2}=0 \qquad (3.11).$$

Taking the Fourier transform we get

$$A(Z,t)=\int_{-\infty}^{\infty}\tilde{A}(0,\omega)\,exp(\frac{i}{2}\beta_2 z\omega^2-i\omega t)d\omega \qquad (3.12).$$

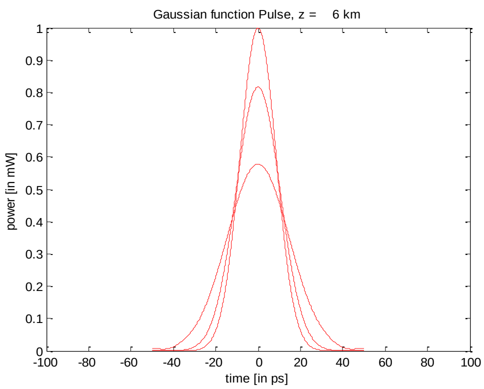


Figure 15: Gaussian Pulse normalized by L_D. Broadening of pulse at 0, 3 and 6 Km having D= 17 ps-nm/km

and $$\tilde{A}(0,\omega) = \int_{-\infty}^{\infty} \tilde{A}(0,t)\, exp(i\omega t)dt. \qquad (3.13).$$

$A(0,t)$ Represent the optical bit stream, to evaluate the effect of dispersion on a pulse we can compare with a Gaussian pulse to known the dispersion effect.

$A(0,t) = A_o exp[(-\frac{1}{2}(1+ iC)(\frac{t}{T_o})^2]$. Here A_o is the peak amplitude C is chirp effect on pulse T_o is the half width at half power point. The full width half maximum of the pulse is

$$T_{FWHM} = (2\sqrt{2ln2}\,.T_o) \approx 1.665T_o \qquad . \qquad (3.14).$$

Chirped pulses are broadened more than non-chirped pulses, but we consider C zero in above equation in our case. The spectral width for the pulse at half power point is generally

$$\Delta\omega_o = \sqrt{1 + C^2/T_o} \qquad (3.14).$$

If C is zero then $\Delta\omega_o T_o = 1$ or $\Delta\omega_o = 1/T_o$. One important characteristics of the Gaussian pulse remain Gaussian before transmission and after transmission but its initial values of pulse width and chirp changes at normalized distance. The pulse width changes from its initial value T_o to T_1 which is the multiple of broadening factor.$= T_o bf\ (\xi)$ (3).

Where $\xi$is the normalized distance it is normalize by the dispersion length L_D, which is $\xi = \frac{z}{L_D}$ and L_D dispersion length dependant on chromatic dispersion $L_D = \frac{T_0^2}{\beta_2}$

The normalized broadening $bf\ (\xi) = [1 + sc(\xi)^2 + (\xi)^2]^{\frac{1}{2}}$, s define the chromatic dispersion is in the normal or anomalous dispersion (+or –). In term of fiber and pulse bf is

$$bf\ (Z) = \left[1 + C\left(\frac{\beta_2 Z}{T_o^2}\right)^2 + \left(\frac{\beta_2 Z}{T_o^2}\right)^2\right]^{\frac{1}{2}} \qquad . \qquad (3.15).$$

Considered for C=0,

$$bf\ (Z) = \left[1 + \left(\frac{\beta_2 Z}{T_o^2}\right)^2\right]^{\frac{1}{2}} \qquad . \qquad (3.16).$$

In absence of chirp chromatic dispersion will depend on the distance because the value of β_2 is linear. The broadening of the pulse during the transmission depends on the fiber length. The transfer function of the fiber and considering only chromatic dispersion,

$$H(f) = \exp(-j2\pi^2\beta_2 z f^2) \qquad (3.16).$$

By increasing the fiber length, the fiber channel will be more dispersive but the transmitted pulse would be detectable to the receiver as long as the fiber length is less than the fiber dispersion length (L_D) (3).

Chapter 4

Theory and implementation of the system model

In this chapter non-coherent direct detection technique for differentially phase modulated systems and reconstruction of received optical field information in electrical domain is discussed. First we will discuss about the basics of coherent and non coherent detection techniques, and then implemented receiver model design for the reconstruction of received optical field information in electrical domain.

2.11 Coherent and Non-Coherent systems

In earlier 70's the optical communication systems were simple. The transmitter consisted of a laser as optical source and intensity modulation as modulation format so that the optical signal could transmit through the optical fiber. Receiver was also simply designed; use square law detection technique for intensity detection and decision circuitry for the decision of detected symbols. The combination of an intensity modulator and direct detection (IM/DD) systems is a type of non coherent system. These systems were successfully deployed and working in existing optical networks. The main advantages in direct detection systems has the simple system design, and no need of a optical local oscillator (OLO) and tracking circuitry for tracking the required reference phase information. Noncoherent systems are also cost effective, consume less power and have less complex design especially for multilevel signaling(12).

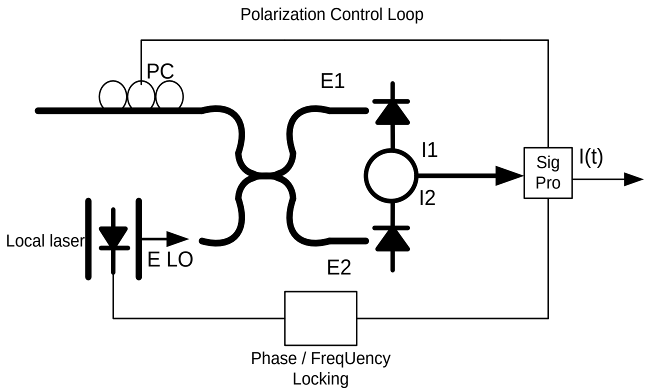


Figure 16: Coherent receiver [8]

Coherent receiver optical systems use the product of a local oscillator and received optical field for the detection of transmitted signal. Coherent receiver uses the homodyne or heterodyne detection design, and called as coherent homodyne or heterodyne receiver.

In figure (16) a coherent receiver is shown. A local oscillator optical field and received optical field are interfering and generating two optical fields E_1 and E_2 as,

$$E_1 = \frac{1}{\sqrt{2}} (E_s + E_{LO}), \qquad E_2 = \frac{1}{\sqrt{2}} (E_s - E_{LO}) \qquad (4.1).$$

The output current

$$I(t) = I_1(t) - I_2(t) = 2R\sqrt{P_s(t)P_{LO}}cos\{\omega_{IF}t + \theta_{LO}(t)\} \qquad (4.2).$$

Where, P_{LO} is the Power of the local oscillator and P_s power of the signal with phase noise, and R is the responsibility(12) (9).

The *self coherent* system is the combination of differential phase shift keying (DPSK) and direct detection scheme. By using the DPSK modulation except PSK it becomes possible to detect the phase of the signal without a local oscillator. The self coherent technique does not need a local oscillator, but it uses the ODI in place of OLO. ODI compare the received pulse with a delayed copy of itself to convert the optical modulation format in to intensity modulated signal before the balance detection. This type of detection scheme utilize in self-coherent DQPSK detection by employing the orthogonal differential techniques. The most common modulation format used for self coherent detection schemes are DBPSK and DQPSK. The generation of DPSK formats is already discussed in detail in chapter 2. Here only DQPSK system has explained in more detail to get the understanding of DQPSK system to understand the implemented model (13) (12) (9).

2.12 System Model Design

As we have discussed earlier, the purpose of this thesis is to implement the idea of field reconstruction and dispersion compensation.

The system design of a RZ-DQPSK transmitter is generally composed of a semiconductor laser, a differential preorder and an optical encoder. A semi conductor laser generates an optical high frequency carrier, which is used for carrying the modulated differential phase information on the optical fiber. The system model is designed and simulated in base band. The input data is generated by the pseudo random binary sequence (PRBS) generator, which is the most commonly, used technique to generate the random binary input data for the simulation of a communication system. The PRBS bits are converted from serial to parallel as a_I bits and a_Q bits to the encoder input. The encoder/or pre-coder generates the differential phase of two adjacent symbols, and then differential phase generate a differentially encoded symbol.[20,23]

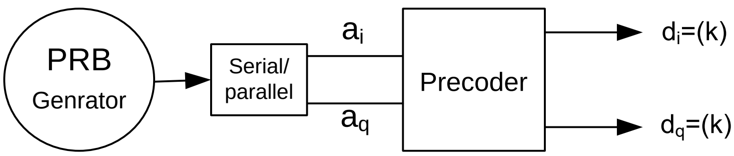


Figure 17: Electrical differential data generation from PRBS

The encoder/ Pre-coder takes the inputs $a_I(k) and\ a_Q(k)$ as shown in figure (17) and generates the $d_Q(k)$ and $d_I(k)$ according to given equations

$d_Q(k) = (a_Q(k) \oplus a_Q(k)) \oplus d_Q(k)$ (4.3).

$d_I(k) = (((a_Q(k) \oplus a_I(k)) \wedge d_Q(k-1)) \oplus a_I(k)) \oplus d_I(k-1)$(4.4)

In the equation $\oplus$is the XOR operator and $\wedge$ is the AND operator, $d_I(k-1)$and $d_Q(k-1)$ are the previous output bits (14).

The output of the pre-coder $d_I(k)$ and $d_Q(k)$ are the input to the dual drive modulator and phase modulator in order to modulate the phases of I and Q components, ϕ_1 and ϕ_2 respectively. The differential phases of the symbol in electrical signals are encoded through the phase modulator (RZ Mod) as shown in the figure(15). In this configuration it becomes necessary to synchronize the dual drive MZM modulator and RZ modulator with the same clock.

Generally, in the electrical domain pulses are generated by the pulse shape generator but optical pulses can be generated by the MZM modulators combination.

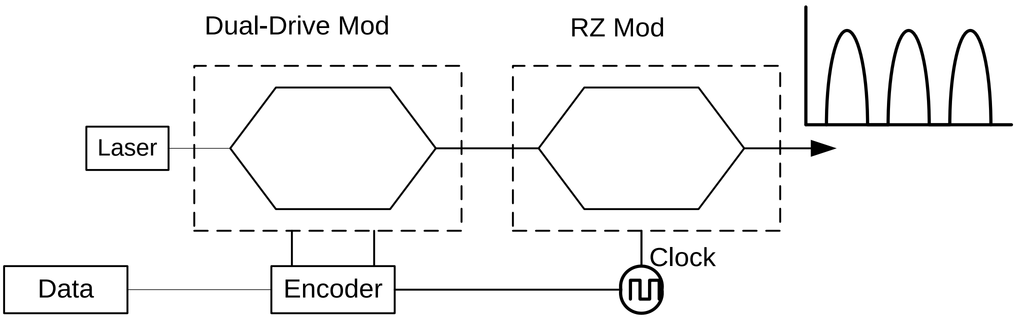


Figure 18: A RZDQPSK transmitter with the combination of DDM and PM. [8]

The dual drive modulators have two independent driving voltages $V1$ and $V2$ and an input electric field E_i to DDM then the output of the dual drive modulator,

$$E_o = \frac{E_i}{2}\left[\exp\left(j\pi\frac{V_1}{V_\pi}\right) + \exp\left(j\pi\frac{V_2}{V_\pi}\right)\right] \quad (4.5).$$

E_o is the output of the dual drive modulator and V_π is the voltage require to generate the 180^0 phase shift. The dual drive MZM perform the phase modulation when modulator drive voltages are ($V_1 = V_2$) equal with phases $\phi_1 = \frac{\pi V_1}{V_\pi}$ and $\phi_2 = \frac{\pi V_2}{V_\pi + \pi}$.

$$E_o = \frac{A_{max}}{2}\left(e^{j\phi_1} - e^{j\phi_2}\right) \quad (4.6).$$

And the output E_o in equation (4.6) would be the difference of the electric field of ϕ_1 and ϕ_2 (when they are antipodal) and MZM's would be biased at the minimum transmission point having maximum electric field amplitude A_{max}(9).

The low pass representation of an optical signal is

$$S(t) = A_s(t)e^{j\phi_s(t)} \quad (4.7).$$

For multilevel DPSK signal, the phase is divided among the different wave forms in even levels but for QAM modulation format both amplitude and phase parameters are used for modulation. The phase difference between the transmitted symbols can be calculated by this equation,

$$\vartheta_n = \pi\,(2n-1)/M \quad . \quad (4.8).$$

Where $n = 1,2,3 \ldots . M$, and M is the number of different wave form or symbols. In this equation any phase offset can be added to adjust the symbol constellation as per required signal space. Actual transmitted signal in the pass band would be

$$S_n(t) = A_s e^{\left(j\frac{\pi(2n-1)}{M}\right)} e^{j\omega_c t} \quad (4.9).$$

Here $A_s = A$ constant amplitude. Expanding the real part of the above equation

$$S(t) = A_s cos\left[\frac{\pi(2n-1)}{M}\right] cos\omega_c t - Asin\left[\frac{\pi(2n-1)}{M}\right] sin\omega_c t \quad . \quad (4.10).$$

The distance between two adjacent symbols would be $\sqrt{2}A\left|\sin\left(\frac{\pi(n-m)}{M}\right)\right|$ and the possible minimum Euclidean distance is $\sqrt{2}A\ sin\frac{\pi}{M}$.

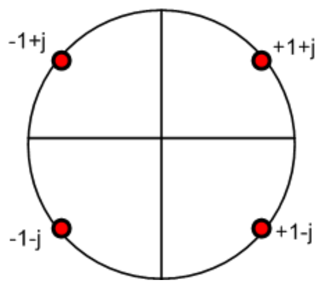


Figure 19: Constellation diagram of DQPSK signal

Both the quadrature modulation formats QPSK and DQPSK use the same equation (4.10) for transmission of the signal, both modulate the four different symbol and differential phase on the corresponding transmitted waveforms. DQPSK modulation format use the complex valued wave forms and each wave form represent symbol. The symbol point on quadrature plain are the $\pm 1\ \pm j$ as shown in table (20).

Alphabets a_n		Constellation points
I bit	Q bit	
1	1	+1+j
0	1	-1+J
1	0	+1-j
0	0	-1-j

Table 12: In table constellation points and inputs bits are shown for DQPSK symbols

If the DDM are driven by the binary inputs $V_1 = \exp\left(j\pi\frac{V_1}{V_\pi}\right)$ and $V_2 = \pm V\pi/2$, then they will generate the outputs ± 1 and $\pm j$ respectively. $V_2 = \pm V_\pi/2$ It is important to control the dual drive MZM's with a biasing voltage so that the peak voltage of the V_1 and V_2 should be identical and have the

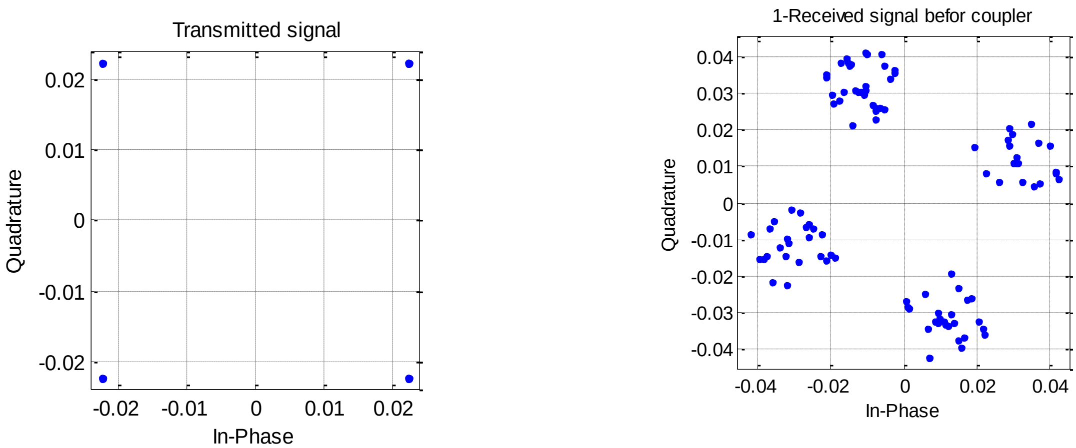


Figure 21: Transmitted DQPSK symbol at distance (a) 0 Km and at (b) 8 Km, the dispersion effects of chromatic dispersion with β_2 =17 ps-nm/Km.

difference of $V_\pi/2$. The drive voltage for dual drive modulator in figure (18) should equal to maximum phase difference of the ϕ_1 and ϕ_2.

Equation (4.10) is the pass band transmission equation but in base band the transmitted signal would be $S(t) = A_s(t)e^{j\phi_s(t)}$. In reality the base band signal is up-converted to pass band in real practical systems, before transmission on the single mode fiber (SMF).

There are many signal degradation phenomena in optical fiber channels but the dispersion effect is considered in this thesis work. In our previous discussion about the group velocity dispersion (GVD) we obtained the following linear expression four wave amplitude and broadening factor,

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = 0 \text{ and } bf\ (Z) = \left[1 + \left(\frac{\beta_2 Z}{T_0^2}\right)^2\right]^{\frac{1}{2}} \qquad (4.11).$$

The broadening of the pulse during transmission through the fiber depends on the distance. The transfer function of the fiber only considering the chromatic dispersion is,

$$H(f) = \exp\left(-j\omega^2 \frac{\beta_2}{2} z\right) \qquad (4.12).$$

In figure (22) due to the dispersion effects symbols point are distorted because chromatic dispersion depend on the distance.

2.13 DQPSK Receiver Design

After transmitting the optical signal it becomes broadened due to the chromatic dispersion along the fiber as modeled by equation (4.12). Before entering the receiver, the optical signal is amplified up to the required optical power level of the receiver. DPSK is the best suitable modulation format for a self coherent receiver. As discussed a self coherent direct detection receiver contains a delay interferometer (ODI) and balance detector and DSP circuitry. In self coherent multilevel modulation with direct detection technique, like DQPSK, uses the same DPSK binary receiver configuration to detect the quadrature modulation components. Each component of the complex received field is identified by the same phase shift.

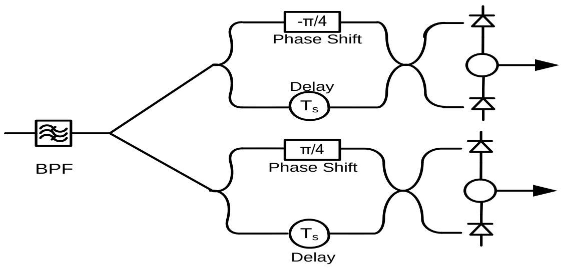


Figure 23: The DQPSK receiver with phase shift or interference angle -π/4 and π/4 configuration.

DQPSK receiver used two delay interferometers for differential demodulation. Although direct detection has the benefits of multilevel signaling, there are also some restrictions on the DQPSK modulation levels. When signal levels increases from DQPSK (4 levels) then it reduces the CD compensation capability which decreases the receiver sensitivity and distance reach. But in non coherent DQPSK the critical phenomenon for signal degradation is dispersion and square law detection. To improve these problems we will use a field reconstruction method in which the received optical field information is reconstructed in electrical domain by DSP. Dispersion compensation was also used to mitigate the dispersion impact on the reconstructed signal [23].

A DQPSK receiver consists of two orthogonal differential delayed receivers and each differential delayed receiver has a ODI, with one symbol duration T_s delay with an interference angle. The interference angles $-\frac{\pi}{4}$ and $+\frac{\pi}{4}$ or 0 and $\frac{\pi}{2}$ can be chosen according to design configuration as shown in figure 23 and 24 respectively. The phase shift between both the ODI's make receiver orthogonal and hence both give orthogonal output, as $dI(t)$ and $dQ(t)$ of received complex optical field. Mathematically we can explain received optical complex field

$$E(t) = I(t) + jQ(t) = E(t)\, exp\,(j\,\phi(t)) \qquad (4.13).$$

In equation (4.13) the received $E(t)$ optical field is the combination of orthogonal complex fields $I(t)$ *and* $Q(t)$ in Cartesian form and in polar form (4.13).

$\phi(t)$ is the phase of received symbol and similarly $\phi(t-T)$ is phase of the previously received symbol and $r(t)$ is the amplitude of the received signal.

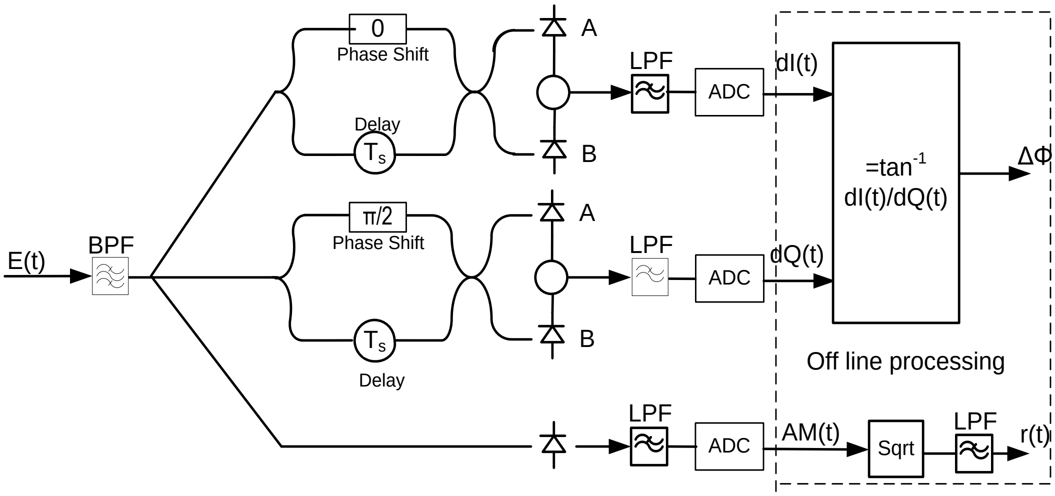


Figure 24: Experimental setup for DQPSK receiver [23]

The output of the two ODI's $dI(t)$ and $dQ(t)$ is given by [21]

$$dI(t) = E(t)E(t-T)\, cos(\Delta\phi(t)) \qquad (4.14).$$

$$dQ(t) = E(t)E(t-T)\, sin(\Delta\phi(t)) \qquad (4.15).$$

But every ODI have one constructive and one destructive branch and their difference is given at the output of the balance detectors.

For the output of $dI(t)$ branch we have

$$\mathrm{E_{01} = \{E_1(t) - E_1(t-T)\}.\frac{1}{2}} \qquad (4.16).$$

$$\mathrm{E_{02} = \{E_2(t) + E_2(t-T)\}.j.\frac{1}{2}} \qquad (4.17).$$

where E_{02} and E_{01} are the constructive and destructive interferences output of the ODI respectively. The output after balanced detection from E_{02} and E_{01} is

$$dI(t) = |E_{02}|^2 - |E_{01}|^2 \qquad (4.18).$$

$$= |Constructive\ Output|^2 - |Destructive\ Output\ |^2.$$

Similarly to make the orthogonal output from second ODI we multiply the $\exp^{j.\frac{\pi}{2}}$ phase shift to get output of $dQ(t)$,

$$E_{11} = \{E_1(t).\exp^{j.\frac{\pi}{2}} - E_1(t-T)\}.\frac{1}{2} \qquad (4.19).$$

$$E_{12} = \{E_2(t).\exp^{j.\frac{\pi}{2}} + E_2(t-T)\}.j.\frac{1}{2} \qquad (4.20).$$

The output of balance detection for $dQ(t)$ is

$$dQ(t) = |E_{12}|^2 - |E_{11}|^2\ . \qquad (4.21).$$

The $dQ(t)$ and $dI(t)$ are the intensity output from the balance detection of both ODI's. It is hard to extract the phase information at this point, since the phase information of the received signal is lost due to the square law detection. First we need to reconstruct the phase information of the received symbols. Generally the differential phase of two adjacent symbols is,

$$\Delta\phi(t) = \phi(t) - \phi(t-T) \qquad (4.22).$$

The process for extracting the differential phase is carried out in DSP.

2.14 Digital Signal Processing (DSP)

In digital self coherent receivers the analog detected waveforms are converted to digital by using high speed ADC after the intensity detection process. The ADC detects the samples at equal time intervals. The delay time of one symbol in the ODI also depends on the number of samples of ADC for a symbol $\frac{T}{sps}$. Here, T is the symbol time duration and sps are the number of samples for an ADC required to detect one symbol. The receiver model in figure (24), ADC's function is applied after detection process on all three dI, dQ and intensity branches. The received optical field can be reconstructed in both digital and analog domain by using offline processing [22]. But in our receiver model the ADC part was skipped and DSP done was done on analog wave forms, of $dI(t)$ and $dQ(t)$ and intensity of received complex optical field as shown in figure (25). This is because we want to study the idealized situation.

The differential phase can be obtained from equations (4.19) and (4.21) as

$$\Delta\phi_n(t) = tan^{-1}\frac{dQ(t)}{dI(t)} \qquad (4.24).$$

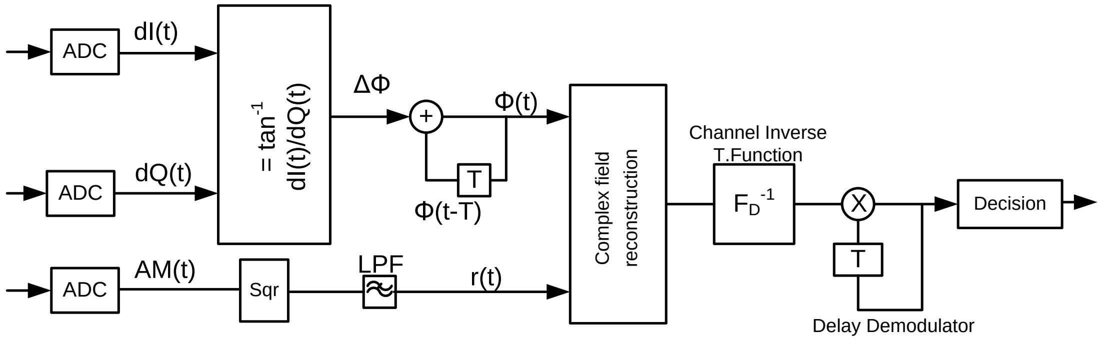


Figure 25: DSP [22]

The resultant phase from equation 4.24 is the reconstructed differential phase field from the received optical field

From figure (25) the 3rd receiver is an intensity receiver which converts the received complex optical field, in to a current. The amplitude of the received signal can be obtained by taking the root mean square of the equation (4.26), the output of intensity receiver (15),

$$P(t) = r(t)^2 \qquad (4.25).$$

Taking the Amplitude of $P(t)$ by taking root mean square, we get

$$r_n = \sqrt{P(t)} \qquad (4.26).$$

The detected amplitude used for reconstruction of the received optical field information as amplitude of the estimated symbol phase. An important point in this receiver design is the absence of a reference symbol or absolute phase. But received differential phase field sequence is built by approximating the reconstructed phase field. Rewriting the equation (4.22)

$$(Diffrential\ Phase)\ \Delta\phi(n) = \phi(n) - \phi(n-1) \qquad (4.27).$$

$$(Symbol\ Phase)\ \phi(n) = \Delta\phi(n) + \phi(n-1) \qquad (4.28).$$

As we know that the differential phase is a rotational phase of one symbol time duration between two symbols. The estimated symbol phases field can be reconstructed by accumulating differential phase, as shown in equation (16).

$$\ddot{\phi}_o = \Delta\phi_o$$

$$\ddot{\phi}_1 = \Delta\phi_1 + \Delta\phi_o$$

$$\ddot{\phi}_2 = \Delta\phi_2 + \Delta\phi_1 + \Delta\phi_o$$

$$\ddot{\phi}_3 = \Delta\phi_3 + \Delta\phi_2 + \Delta\phi_1 + \Delta\phi_o$$

$$\ddot{\phi}_4 = \Delta\phi_4 + \Delta\phi_3 + \Delta\phi_2 + \Delta\phi_1 + \Delta\phi_o$$

.

.

.

$$\ddot{\phi}_n = \Delta\phi_{n-1} + \Delta\phi_{n-2} + \ldots . \Delta\phi_4 + \Delta\phi_3 + \Delta\phi_2 + \Delta\phi_1 + \Delta\phi_o.$$

$$\ddot{\phi}_n = \Delta\phi_n + \Delta\phi_{n-1} + \Delta\phi_{n-2} + \ldots . \Delta\phi_4 + \Delta\phi_3 + \Delta\phi_2 + \Delta\phi_1 + \Delta\phi_o \qquad (4.29).$$

Here n is the no of received symbols, and $\ddot{\Phi}_n$.is the estimated symbol phases extracted from differential phase accumulation shown in above equations (4.29)

From equation (4.27) $\ddot{\phi}_n$ can be also be written as $\ddot{\phi}_n = \Delta\phi_n - \phi_0$

Here ϕ_0 is first symbol phase. The full information of the received optical field can be reconstructed by this technique except the initial phase $\ddot{\phi}_o$ [22]. If we transmit first known symbol before the data symbols and consider it as reference symbol then it could be possible to extract the field of first data symbol estimated phase $\ddot{\phi}_1$. By employing the known reference symbol phase, error margin can be decreased as compared to unknown initial phase in reconstructed received field information. If error occurred in reconstructed phase field after the first symbol phase field then the error will be accumulated in every next estimated symbol phase field. Hence the accuracy of reconstructed field could be lower by using the accumulation process. The error in estimated phase field could arise when reconstructed field is not sampled correctly by ADC due to higher degradation in received symbols (17).

By combining the estimated $\ddot{\phi}_n$ and amplitude field r_n, the actual received optical field information can be reconstructed in electrical domain.

$$\hat{E}(t) = r_n exp^{j\phi_n} \qquad (4.30).$$

$\ddot{E}(t)$ is the reconstructed information of received complex optical field in equation 4.29. Once field information of the received optical signal has been reconstructed then it become easy to compensate the reconstructed signal by applying any suitable compensation technique. In our receiver model we have used the numeric compensation technique / channel inverse transfer function for compensation.

2.15 Compensation

It is necessary to understand the concept the of compensation technique which is applied in this model. As we know the received signal at receiver in the frequency domain.

$$\mathrm{E}(\mathrm{Z},\omega) = \mathrm{E}(\mathrm{U},\omega)\,.\,\mathrm{H}(\mathrm{Z},\omega) \qquad (4.31).$$

Where $E(\omega)$ and $U(\omega)$ are the received and transmitted signal respectively in spectral domain and $H(\omega)$, is the transfer function of the fiber channel.

The basic model for a linear channel of a SMF is shown in figure (26)

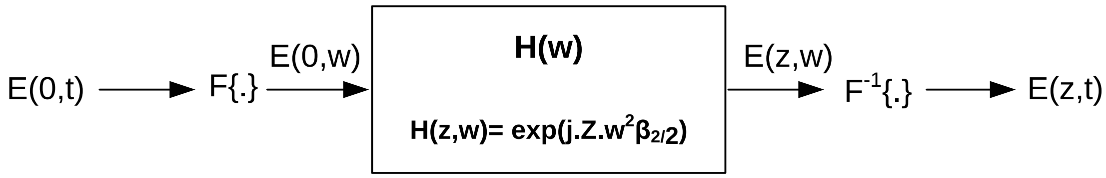


Figure 26: A common SMF Equivalent model

Here $F\{\cdot\}$ is the Fourier transform of the transmitted signal $E(0,t)$ and $F^{-1}\{\cdot\}$ is the inverse foureier transform of the optical complex signal E(z,w).the output signal of the fiber after the fiber channel (18).

$$E(z,t) = {}^{-1}\{F(\{E(0,t)\}\{H(\omega)\})\} \qquad (4.32).$$

From the above equation the equalization or chromatic dispersion compensation is based on the principal that the product of channel response with its inverse would be unity.

$$H(\omega)H^{-1}(\omega) = 1 \qquad (4.33).$$

The unity output of the equation (4.33) is due to the channel inverse characteristics are not changed. The compensation or channel equalization model would be on the same principle. The reconstructed electrical field can be compensated as shown in the figure (27).

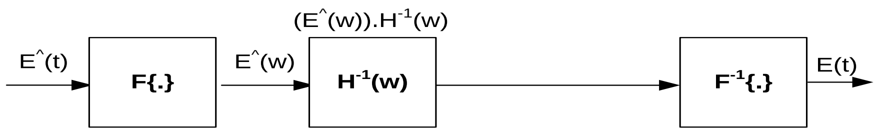


Figure 1327: Compensation model or channel equalization model.

Here the reconstructed field is $\ddot{E}(t)$ and $E(t)$ is compensated field. To get better result of compensation the channel inverse response could be used as a multi stage FIR filter. The channel response is a linear function and a time invariant filter can be designed. If this technique is applied with polarization compensation technique then it gives better results (17).

Chapter 5

Results and Discussion

In this chapter we will discuss the obtained results from our implemented model. After implementing this model the objectives of this thesis work (the reconstruction and compensation) were obtained by using the matlab simulation tool. First we will we will analyze the reconstruction phase field process and then we will discuss compensation simulation results of reconstructed complex electrical signal.

2.16 Optical field Reconstruction for Non-Coherent Direct Detection Systems:

In the digital signal processing part, the first task was to recover the actual received differential phase field information after the balanced detection process. The balanced detection process used the square law detection method, in result we lost the received symbols differential phases information. In first stage we have calculated the rotational angle $\Delta\phi_n(t)$ of one symbol delayed duration of the received field using

$$\Delta\phi_n(t) = tan^{-1}\frac{dQ(t)}{dI(t)} \qquad 5.1.$$

In figure (28) the orthogonal ODI's and the outputs of balance detectors $dI(t)$ and $dQ(t)$ are shown. The ODI's have the same received optical field input only addition difference of $\pi/2$ phase shift to make both ODI's orthogonal. It has been observed that for the reconstruction of differential phase$\Delta\Phi_n(t)$ it is necessary that we have at least two orthogonal amplitude outputs. The same non coherent DQPSK receiver design can be used for DPSK modulation format. But it may be

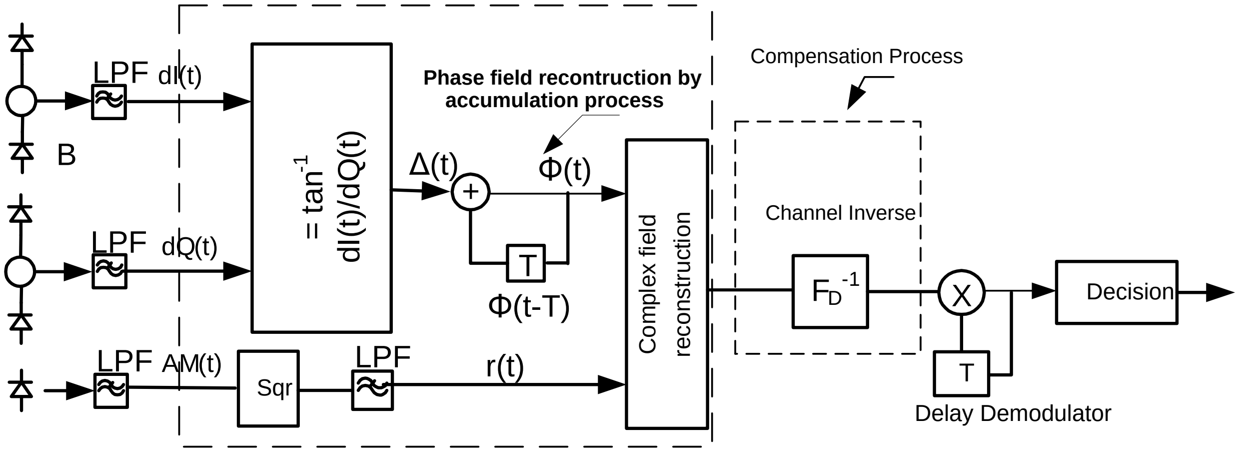


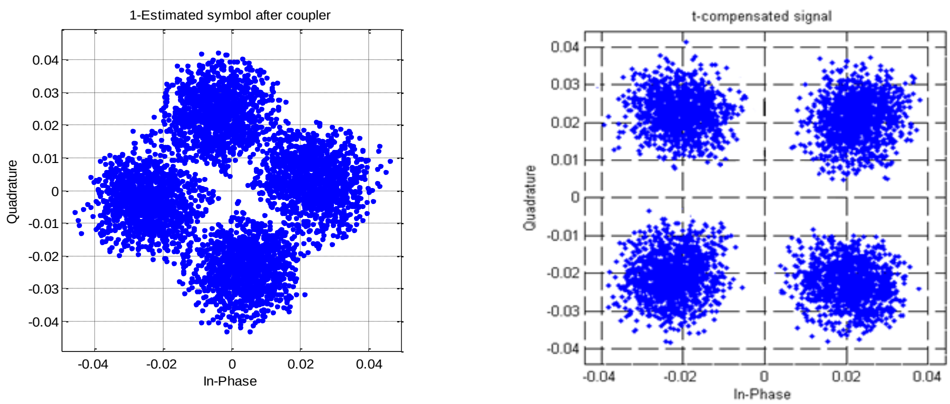
Figure 28: A complete model of non coherent receiver offline processing.

necessary the modulated pulses angle should be orthogonal. The lost received optical signal was then recovered by using the orthogonal outputs of the balance detectors. The transmitted signal power was 1 m Watt. Some of the reconstructed symbol phases were also changed due to the dispersion effects as shown in the received angle column in Table 1.1. in appendix. Phase information was however partly restored after compensation.

The obtained results are showed on scattering plots and eye diagrams of non coherent differentially modulated DQPSK and BDPSK systems. Finally, we have compared the transmitted and reconstructed phase field.

2.17 Plots of DQPSK

First we have transmitted the 40Gbps data rate for DQPSK modulated system the maximum transmission range was found around 15.5 Km after compensation in figure 29.



(a) (b)

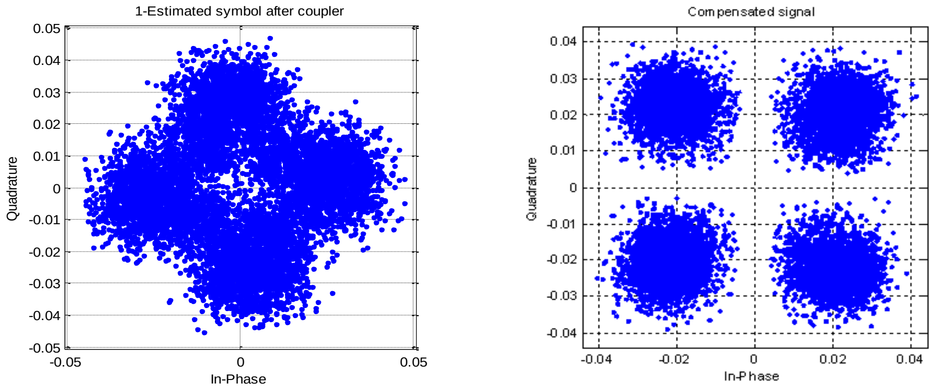
Figure 29: The scattering plot of DQPSK of 40 Gbps at 15.5Km. Estimated or reconstructed symbols (a) Compensated Symbol 60 Gbps(b).

The reconstructed symbols were found scattered and distorted. After compensation symbol noise due to dispersion effect was mitigated. The eye diagram are showing that after compensation symbol noise is mitigated after compensation and symbol decision region is also increased as shown in fig. 30 a-c.

(a) (b) (c)

Figure 30: The eye-diagrams of 40 Gbps DQPSK at 15.5Km. Transmitted symbols (a) Estimated or reconstructed symbols (a) Compensated Symbol (b)

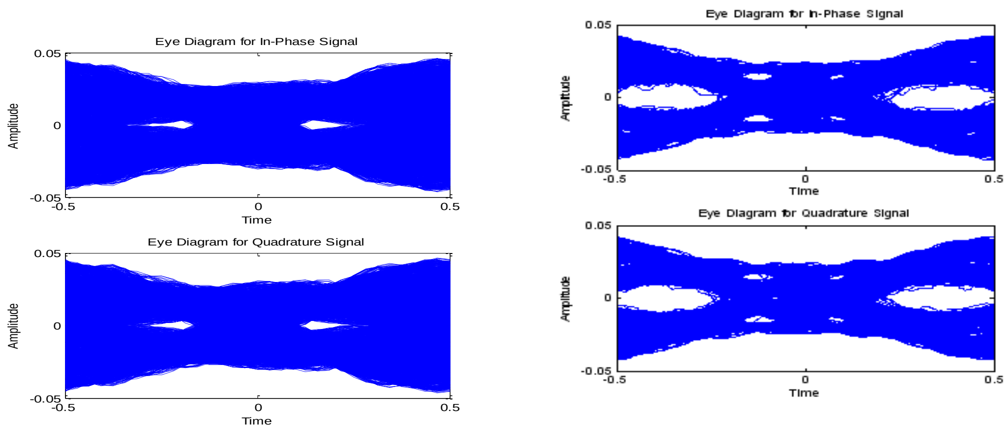
Then we have transmitted symbols at 60Gbps.data rate and we achieved maximum transmission length 6.5 Km, The reconstructed symbols were noisy and scattered as shown in figure (31-a), it was very noisy then we reconstructed the received symbol but noise impacts was approximately same, as shown in 31-b



(a) (b)

Figure 31: The scattering plot of DQPSK of 60 Gbps at 6.5Km. Estimated or reconstructed symbols (a) Compensated Symbol (b)

The eye diagram of 60Gbps data transmission is given in fig. 32-b



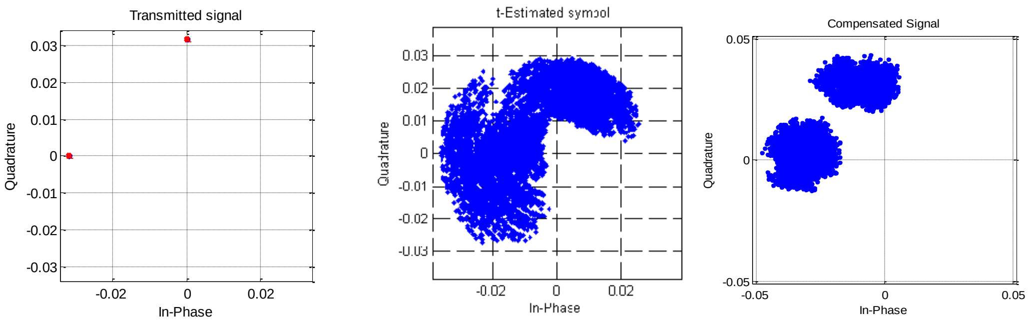
(a) (b)

Figure 32: The scattering plot of DQPSK of 60 Gbps at 6.5Km. Estimated or reconstructed symbols (a) Compensated Symbol (b)

The transmission distance was reduced up to 6.5 Km, so by increasing the data rate noise impact increased and transmission distance also reduced. In last step channel inverse compensation is applied then it become so improved that it could be possible to make the decision region between the symbols.

2.18 Plots for DPSK

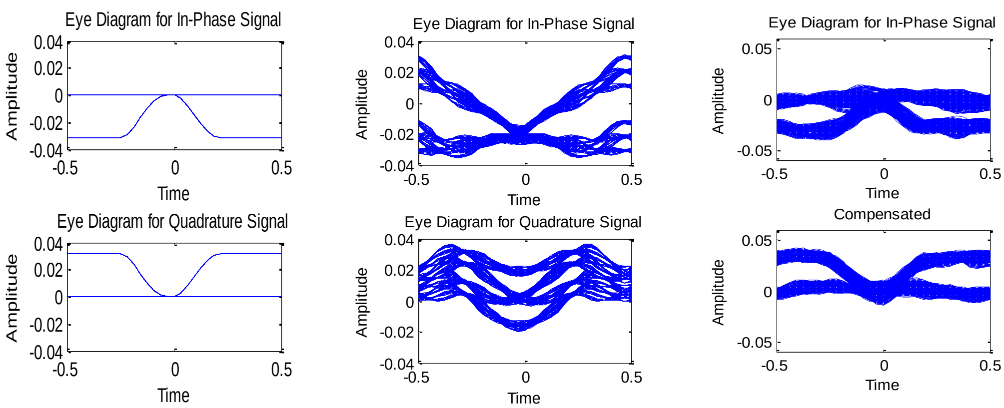
We have used the same DQPSK non-coherent receiver design for non coherent differentially phase modulated DPSK system. We have only changed the differential angle for bits 0 with $pi/2$ and 1 bit with pi to make the transmitted signal orthogonal. This modulation scheme is known as orthogonal DPSK modulation. As we can see the symbol distance are not like normal DPSK based on 3db extra signal bandwidth.



(a) (b) (c)

Figure 33: DPSK 20 Gbps at 17 Km. Transmitted symbols (a) Reconstructed or estimated symbols. (b) Compensated symbols (c)

The reconstructed field was more noisy in this case and after compensation the signal become improved at 17 Km, of fig 33.

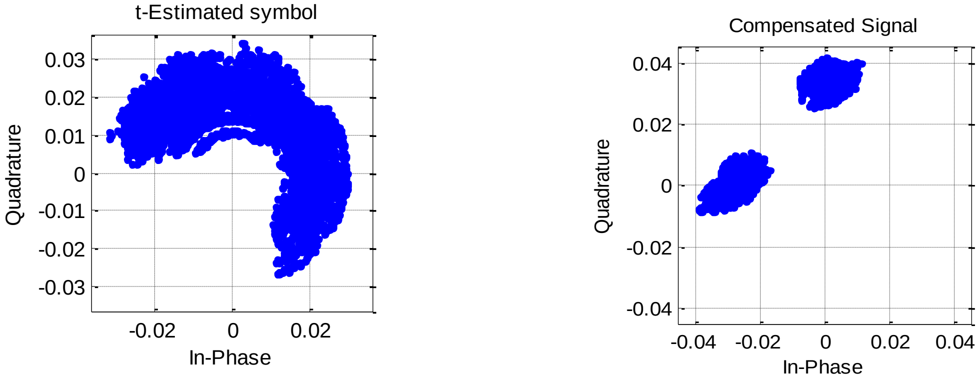


(a) (b) (c)

Figure 37: DPSK 10 Gbps at 55 Km. Transmitted symbols (a) Reconstructed or estimated symbols. (b) Compensated symbols (c)

The eye diagrams are shown in fig 37. As shown in figure (37 b) the eye is closed but it is improved after compensation.

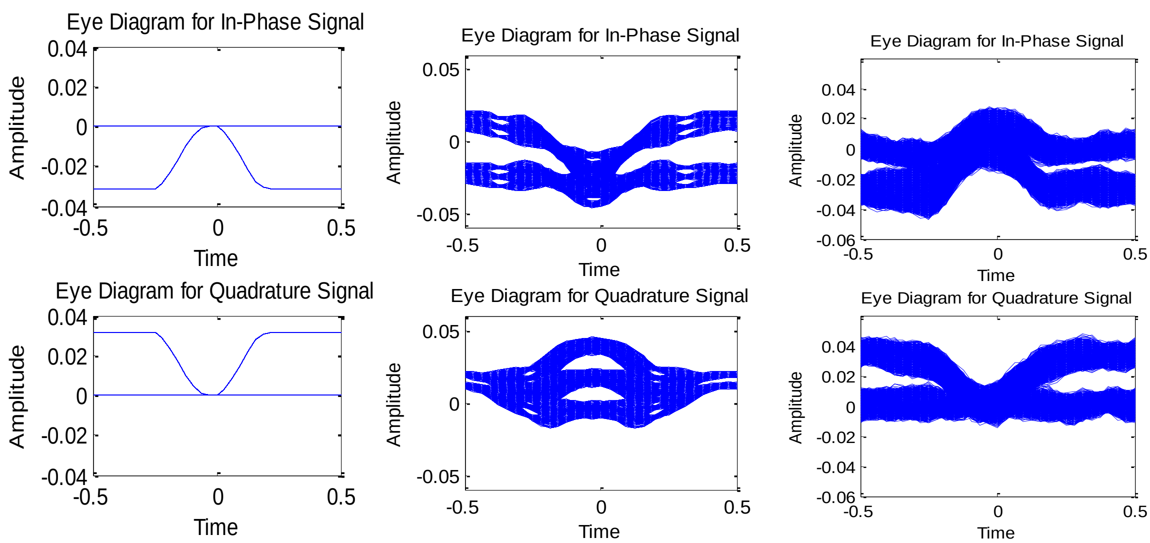
Then we have transmitted data at the rate of 20 Gbps but maximum achieved transmission distance



was around 17 Km. By increasing the data rate the transmission distance was reduced.

(a) (b)

Figure 38: DPSK 20 Gbps at 17 Km. Reconstructed or estimated symbols. (a) Compensated symbols (b)



(a) ***(b)*** ***(c)***

Figure 39: The eye diagram of 10Gbps at 55Km with dispersion.(a)Compensated signal.(b) Transmitted signal (c)

As show in fig 38 and 39 eye-diagram the signal was distorted with chromatic dispersion but after applying the compensation the chromatic dispersion effect and ISI impact was reduced.

The DQPSK and DPSK compensated symbols are still have little scattering, which is due to the unavailability of absolute phase and also due to phase slips.

2.19 Transmitted Phase and Reconstructed Phase Field

In fig. 40 we show reconstructed phases. Transmitted differential phase curve is red and reconstructed phase is in blue color without dispersion.

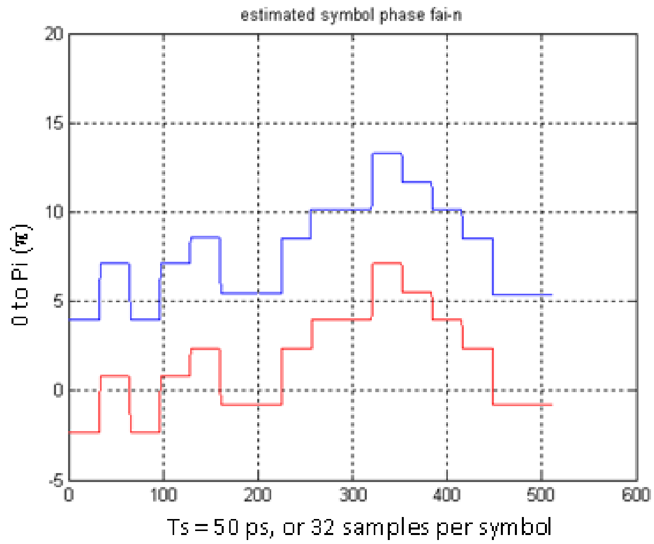


Figure 40: Phase curve of transmitted symbols in red and reconstructed in blue, without dispersion

In figure (40) it is shown that reconstructed phase curve is following the transmitted phase curve with absolute phase gap when fiber channel is noise less.

In figure (41) transmitted phase red curve and reconstructed phase in blue curve are shown,

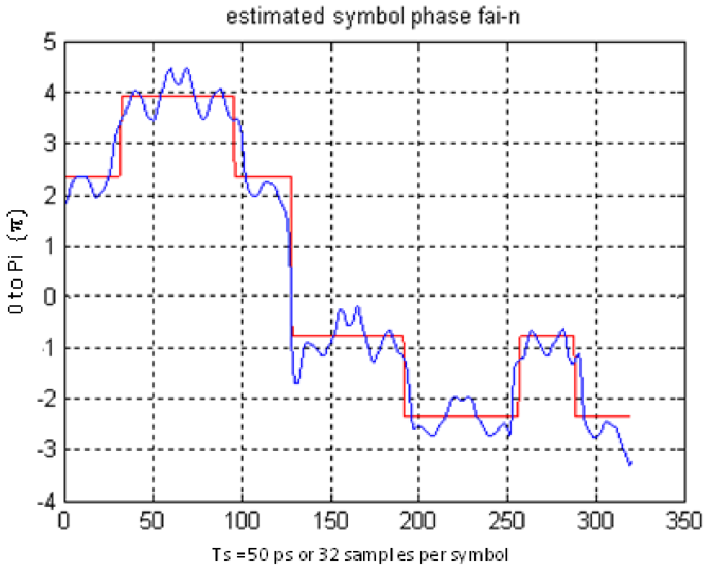


Figure 41: Phase curve of transmitted symbols in red and reconstructed in blue, with dispersion.

It is shown in the figure (40) transmitted signal phase field and reconstructed phase has the uniform phase gap. The initial estimated phase $\ddot{\phi}_n = \Delta\phi_n - \phi_0$, so $\ddot{\phi}_n$ contained the absolute phase ϕ_0 which is missing for $\ddot{\phi}_n$. So from the start of the reconstructed phase curve there is a constant phase gap due to ϕ_0 .In figure (41) the reconstructed phase sequence is not uniform due to the dispersion effect but reconstructed curve is following the transmitted symbol phase sequence.

Reconstructed curve shows that the reconstructed phase field information is correctly constructed in electrical domain.

Appendix

1	2	3	4	5	6	7
I bit	**Q bit**	**Transmitted signal phase**	**Received angle phase**	**Calculated Δϕ (t)=tan^{-1} (dQ(t))/(dI(t))**	**Reconstructed Symbol phase field $\Delta\ddot{\phi}$**	**Compensated signal phase**
1	*1*	*0.7854**	*0.8321**		*0.8321**	*0.7891 **
1	1	0.7854	0.8405	0.8405	0.8405	0.7976
0	1	2.3562	2.4027	1.5621	2.4027	2.3371
0	1	2.3562	-3.8802	0.0004	2.4030	2.2685
1	0	-0.7854	-0.7450	3.1352	-0.7450	-0.8232
0	0	-2.3562	-2.3074	-1.5624	-2.3074	-2.2661
0	1	2.3562	-3.8696	-1.5621	-3.8696	2.3729
0	0	-2.3562	-2.3095	1.5601	-2.3095	-2.3366
0	0	-2.3562	-2.3094	0.0001	-2.3094	-2.4451
1	1	0.7854	0.8259	3.1352	-5.4573	0.7518
1	0	-0.7854	-0.7279	-1.5538	-7.0111	-0.6889

Table 2: DQPSK transmitted symbols phases comparison at different stages from TX to RX. *First symbol is reference symbol.

Conclusion

In this diploma project orthogonal field reconstruction and numerical compensation techniques has been studied and implemented for non-coherent direct detection systems. It was observed that the m-array phase modulated formats can be used in non-coherent direct detection systems. In non coherent direct detection systems the major problem was the loss of the phase information after intensity detection and EDC could not be done properly because of unavailability of correct phase. But it was proposed to solved this by the orthogonal field reconstruction method. The received optical field was then reconstructed out of ODI's and one extra amplitude branch followed by DSP. In the whole receiver design, offline processing performs the major role. The offline processing performed the phase extraction from the intensity branch and they gave the differential phase information by phase accumulation process. When the differential phase field information was recovered then it was easy to reconstruct the optical received complex signal information in electrical domain by multiplying the amplitude branch with the reconstructed differential phase information.

It was observed that the reconstructed field information was not error free because of the accumulation process, errors were accumulated in the incoming symbol sequence. Once the received signal information was reconstructed, then it was possible to reduce the dispersion effects from reconstructed field information by applying the numeric compensation technique. These symbol phase errors arise due to chromatic dispersion It was also observed that when the transmission length was increased by its dispersion length L_D it became hard to reduce the errors due to increased chromatic dispersion effects. After employing the numeric compensation for RZ-DQPSK system for 40 Gb data rate the transmission length was increased by its calculated dispersion distance limit 10.4 Km to around 17Km. Similarly for the same design of the receiver 60 Gb data rate has been transmitted at the maximum transmission length of 7Km. From the eye diagrams in chapter 5 it was shown that the numeric compensation removed the major dispersion effects from the received signal, also caused to enhance the decision region area.

The same receiver design of RZ-DQPSK was used for binary DPSK. Transmitted DPSK modulation format was orthogonal so it becomes feasible to use the DQPSK receiver for the DPSK modulation. Two data rates of 20Gbps and 10Gbps for orthogonal DPSK modulation were transmitted, and their transmission lengths were around 17 km and 55Km respectively. Their transmission distances were also increased by their higher dispersion length L_D. It was observed in orthogonal DPSK modulation chromatic dispersion effects were more swear then ordinary DPSK modulation due to 3 dB less distance between the symbols.

Now it become more straightforward for the non coherent direct detection receivers to overcome their poor performance of EDC due to loosing the phase information, by applying the orthogonal field reconstruction and numeric compensation method. As a result EDC at the receiver side almost perform well compare to the EDC at transmitter side. If DSP accumulation process is made free from error accumulation by employing any technique then receiver side EDC can be imposed. By employing a better compensation technique dispersion can be further reduced to increase the transmission length.

Other channel impairments like PMD and SPM can be reduced from received signal after field reconstruction in non coherent direct detection systems which we believe can be an area of future studies.

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