Investigation of Different Optical Modulation Schemes

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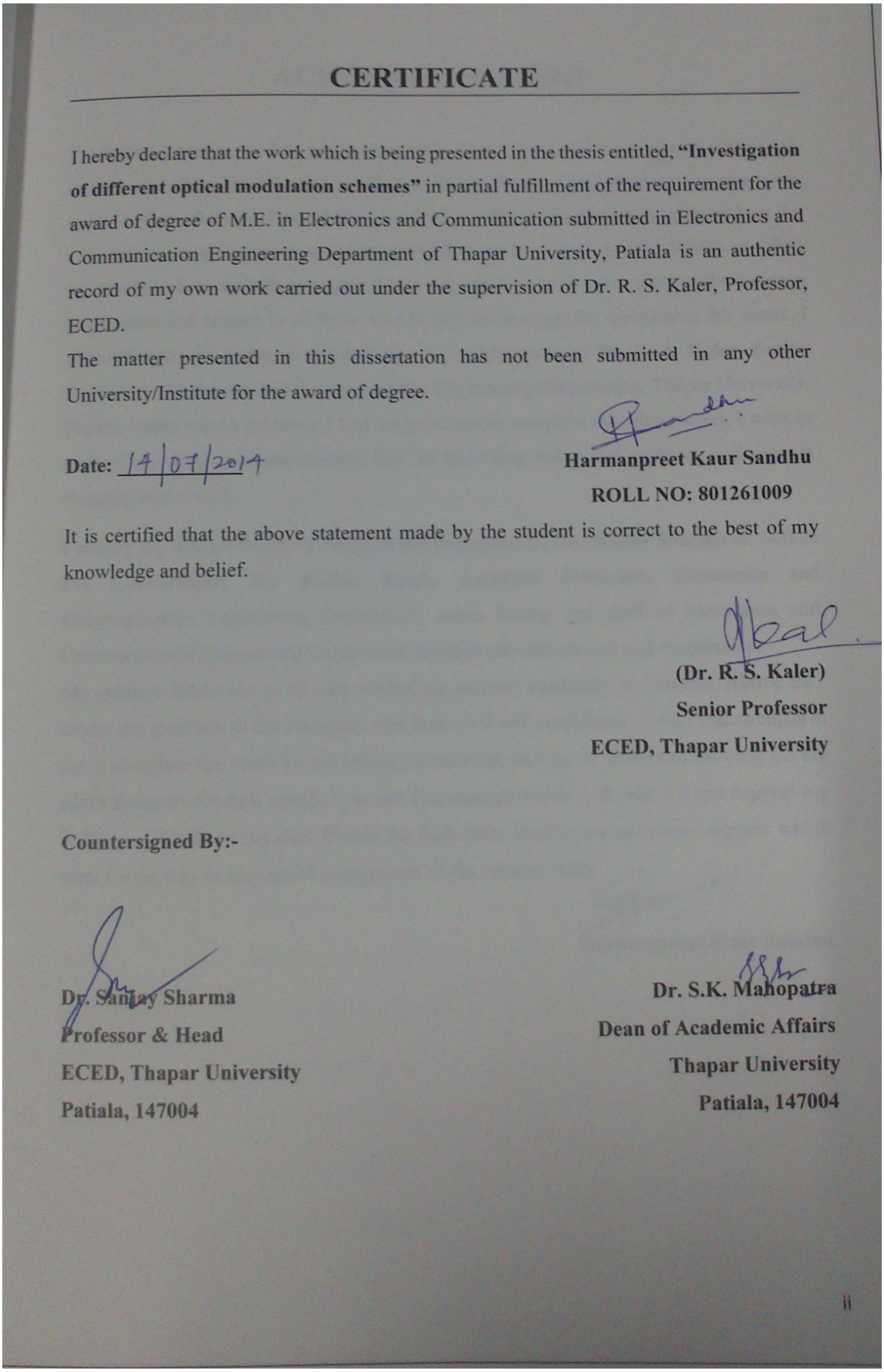

CERTIFICATE

I hereby declare that the work which is being presented in the thesis entitled, **"Investigation of different optical modulation schemes"** in partial fulfillment of the requirement for the award of degree of M.E. in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of Dr. R. S. Kaler, Professor, ECED.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABBREVIATIONS

WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
CD	Chromatic Dispersion
PMD	Polarization Mode Dispersion
FWM	Four-Wave Mixing
SPM	Self-Phase Modulation
XPM	Cross-Phase Modulation
ASE	Amplified Spontaneous Emission
EDFA	Erbium-Doped Fiber Amplifier
NRZ	Non-Return-to-Zero
OOK	On-Off Keying
FEC	Forward Error Correction
DPSK	Differential Phase Shift Keying
RZ	Return-to-Zero
DQPSK	Differential Quadrature Phase Shift Keying
POLMUX / PM	Polarization Multiplexing / Polarization Multiplexed
OSNR	Optical Signal to Noise Ratio
ASK	Amplitude Shift Keying
PSK	Phase Shift keying
FSK	Frequency Shift Keying
PolSK	Polarization Shift Keying
IM	Intensity Modulation

MZM	Mach-Zehnder Modulator
DFB	Distributed Feedback
PSD	Power Spectral Density
CS	Carrier-suppressed
PM	Phase Modulator
MZI	Mach-Zehnder Interferometer
CI	Constructive Port
DI	Destructive Port
GVD	Group Velocity Dispersion
AMI	Alternate Mark Inversion
QPSK	Quadrature Phase Shift Keying
BPSK	Binary Phase Shift Keying
PDM	Polarization Division Multiplexing
DAC	Digital-to-Analog Converter
LO	Local Oscillator
ADC	Analog-to-Digital Converters
DSP	Digital Signal-Processing
XpolM	Cross-Polarization Modulation
SOA	Semiconductor Optical Amplifiers
DFBP	Digital Filter-based Back-propagation
QAM	Quadrature Amplitude Modulation
EVM	Error Vector Magnitude
DGD	Differential Group Delay
NLP	Non-linear Phase

SEP	Symbol Error Probability
PS	Polarization Switched
SSMF	Standard Single Mode Fiber
BER	Bit Error Rate
DM	Dispersion Managed
DBP	Digital Back-propagation
SOP	State of Polarization
HDTV	High Definition Television
TDM	Time-Division Multiplexing
PON	Passive Optical Networks
FIR	Finite Impulse Response
FFT	Fast Fourier Algorithm
DFT	Discrete Fourier Transform
I-Q	In-phase and Quadrature
DOP	Degree of Polarization
CW	Continuous Wave
PBS	Polarization Beam Splitters
MUX	Multiplexer
SMF	Single Mode Fiber
LPF	Low Pass Filter
PRBS	Pseudo Random Binary Sequence
LHC	Left-handed Circularly
RHC	Right-handed Circularly

ABSTRACT

The optical communication system has become a major part of global infrastructure in the past years because of its several benefits. The main objective of an optical communication system is to utilize minimum bandwidth over long distances with minimum possible errors during the transmission of signals. Today, the core of the telecom network consists of optical Wavelength Division Multiplexed (WDM) systems as it provides an advantage of high spectral efficiency (defined as the overall transmitted capacity per unit bandwidth). The commercial WDM systems provided a spectral efficiency of 0.2-0.8 b/s/Hz but in order to cope up with the exponential increase in demand of capacity due to fast growth in telecommunication industry, there is a need to develop communication systems with higher spectral efficiencies. Traditionally, optical communication systems employed on-off keying (OOK) as its modulation format but it is no more a suitable choice for next generation optical transmission systems. So choosing an appropriate modulation scheme for the optical transmission systems that can provide higher capacities at high data rates is a critical issue. While selection of an optical modulation scheme, there is a trade-off between various requirements, namely Optical Signal to Noise Ratio (OSNR) requirement, optical filter tolerance, spectral efficiency, Chromatic Dispersion (CD) tolerance, Polarization Mode Dispersion (PMD) tolerance, non-linear tolerance and transponder complexity. Each of these requirements has a different importance which depends on the design of the optical transmission system. This necessitates the designer to have an optimal choice of optical modulation scheme.

The objective of this dissertation is to investigate the performance of different optical modulation schemes by means of numerical simulations. In order to achieve this goal, first of all, different optical modulation formats, namely, OOK, Differential Phase Shift Keying (DPSK), non-return-to-zero Differential Quadrature Phase Shift Keying (NRZ-DQPSK) and return-to-zero (RZ) DQPSK have been compared with each other at different data rates. The results showed that RZ-DQPSK gives the best performance at high data rates. Secondly, the performance of dual carrier polarization multiplexed (POLMUX) DQPSK at 112 Gb/s with respect to changes in state of polarization (SOP) and the differences between two formats (RZ and NRZ) of POLMUX DQPSK signal have been analysed. The POLMUX RZ-DQPSK systems gave an improvement of 1.25 dB in OSNR for BER=10^{-3}

than POLMUX NRZ-DQPSK system. Thirdly, the impact of cross-phase modulation (XPM) and cross-polarization modulation (XpolM) imposed by OOK or DPSK channels was investigated on a 112 Gb/s POLMUX QPSK signal along with increase in number of channels and increase in bit rate. A hybrid WDM system consisting of alternate channels of OOK and DPSK signals with 50 GHz spacing between them was also proposed to minimize the impact of XPM by OOK channels.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION:

Optical fiber communication is a prominent name in the dictionary of communication field. It is a technique in which information is transmitted from the transmitter to the receiver side by propagation of light through an optical fiber. It plays a key role in the telecommunications industry due to its several advantages over electrical transmission. In the developed areas, copper wire communications has been replaced by the fiber-optic communication. High data-carrying capacity, exceptionally low loss and coverage of long distances between repeaters or amplifiers are some of the merits of using an optical fiber. So in order to replace a single high bandwidth optical fiber, thousands of electrical links would be needed. Also, in contrast to electrical transmission lines, fiber-optic cables experience less or no crosstalk when they run alongside each other to cover long distances.

The initial deployment of fiber-optic networks was mainly for long-haul transmission but now they are currently being deployed in almost all metro-networks [1]. Thus, the high demand for capacity in regional, national and even metropolitan optical networks calls for the upgradation of the existing backbone communication networks to utilize higher transmission rates. In order to further improve the overall capacity of the system, the number of channels per fiber also needs to be increased which can be accomplished by the use of Wavelength Division Multiplexing (WDM) or Dense WDM (DWDM). But the linear and non-linear impairments become worse in such high-speed DWDM networks. Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) are the linear impairments; and the non-linear impairments include Four-Wave Mixing (FWM), Self-Phase Modulation (SPM) and Cross-Phase Modulation (XPM).

An optimal modulation scheme is required to minimize the degrading effects that exist due to impairments in the fiber. An optical modulation scheme/format with a narrow optical spectrum can tolerate more CD distortion and increase spectral efficiency. The distortions induced by CD and PMD can be reduced by using modulation formats employing multiple signal levels, that have longer symbol duration and carry more information than binary signals. Also, a modulation scheme with constant optical power would be less vulnerable to SPM and XPM. The modulation formats are required to be more tolerant to additive Amplified Spontaneous Emission (ASE) noise which is produced by Erbium-Doped Fiber Amplifiers (EDFA) in long-haul networks. Extensive research efforts have been made in the last years so that enabling technologies become mature for these formats [2-6]. Hence, in order to realize optical networks with high spectral efficiencies that can provide huge capacity, these advanced modulation schemes are crucial along with other technologies such as forward error correction techniques, optical amplifiers which produce less noise and new advanced range of optical fibers.

1.2 BACKGROUND

Over history, the development of optical fiber communication has mainly concentrated on reducing the losses in optical fibers along with inventing a range of optical fiber amplifiers. The resulted in the advent of WDM technology in early 1990's. Initially, WDM was performed for intensity modulated signals with direct detection that allowed different channels to be densely packed which resulted in efficient utilisation of the available bandwidth by mid-1990's. But following the "bubble burst" of the early 2000's that witnessed the evolution in communication field, bandwidth became a limited and precious resource. Thus, in order to fulfil the today's on-going demand for greater capacity, modulation formats with high spectral efficiency have become the need of the hour.

1.3 MOTIVATION

The modulation format defines the characteristics of an optical signal which is transmitted over the transmission link. Until few years, the choice of optical modulation format for nearly all optical transmission systems was Non-Return-to-Zero On-Off Keying (NRZ-OOK). NRZ-OOK used a cost-effective transmitter and receiver architecture which had a transmission performance that was sufficient to realize 10-Gb/s transmission systems. But over the past 25 years, the transmission rate of data that can be achieved by optical fiber communication networks has increased by four times in magnitude [7] and the transmission tolerances of NRZ-OOK modulation format are too small to realize long-haul transmissions at bit rates of 40-Gb/s or 100-Gb/s.

Also, the currently installed optical fibers both under the ocean and underground are multi-billion dollar investments and it would be expensive to install more fibers in order to fulfil the traffic demands. Therefore, we seek methods which utilize the already available resources. The systems have already used a very wide spectrum of frequencies by the deployment of WDM systems that rapidly approached 10 Tb/s and for further expansion in their frequency range, hardware limitations started to become crucial. These limitations include the bandwidth of optical amplifiers, the frequency selectivity of optical filters and the wavelength stability of semiconductor lasers [8]. Hence, new systems to increase spectral efficiency should be designed. The achievable spectral efficiency of binary modulation formats is restricted to 1-b/s/Hz [9] theoretically while in practical systems, it is significantly lower than 1-b/s/Hz since WDM system is considered to be transparent, which means that the crosstalk from the nearby channels is taken to be unknown, therefore it is considered as a noise source. There is further reduction in spectral efficiency due to other system design aspects that includes the 7% overhead which is usually required for Forward Error Correction (FEC), limited filter order of optical filters as well as wavelength drift in the (de-)multiplexing filters and transmitter laser. Hence, the feasible spectral efficiency of NRZ-OOK is approximately <0.7-b/s/Hz due to the restrictions imposed by the required margins.

The 40-Gb/s transmission systems currently deploy modulation formats which are more adherent to transmission impairments than NRZ-OOK. The tolerance against CD and narrowband optical filtering can be improved by using duobinary format. But the most widely employed state-of-the-art modulation format is phase modulation, using Differential Phase Shift Keying (DPSK).These schemes are more tolerant towards narrowband optical filtering and have a spectral efficiency of up to 0.8-b/s/Hz. Multi-level modulation formats, such as Return-to-Zero Differential Quadrature Phase Shift Keying (RZ-DQPSK) modulation, with 2 bits per symbol can increase this efficiency up to ~1.6-b/s/Hz. In addition it is more tolerant to narrowband optical filtering as well as many linear transmission impairments. Polarization Multiplexing (POLMUX) is another potential candidate that can be used to reduce the symbol rate. POLMUX signalling when combined with DQPSK modulation, enables modulation of signals with 4 bits per symbol.

Multi-level modulation is the most suitable solution for 100-Gb/s transmission. The use of 100 Gb/s NRZ-OOK has been demonstrated in [10] but it pose some serious issues in deployed transmission systems due its low CD and PMD tolerance as well as high Optical Signal to Noise Ratio (OSNR) requirement. Therefore, DQPSK is more likely candidate for long-haul transmission at 100-Gb/s as the bandwidth requirement of the electrical

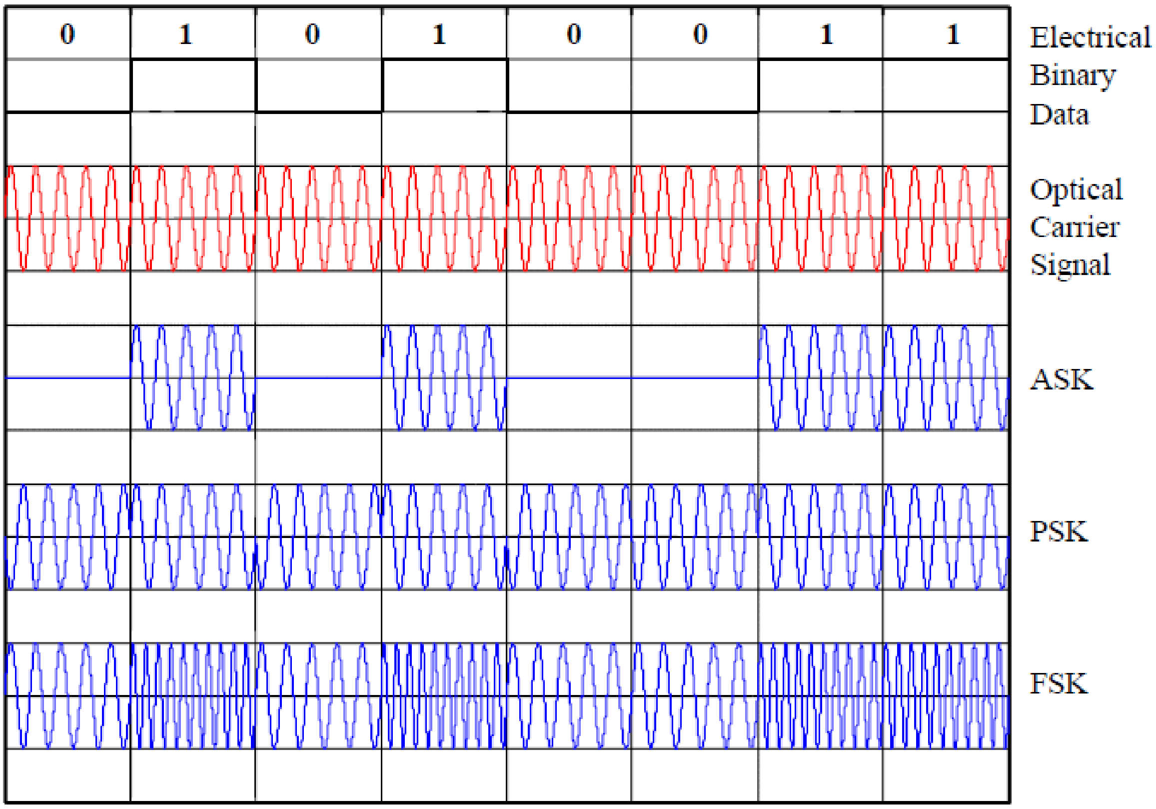


Figure 1. 1 Basic digital modulation formats (ASK, PSK, FSK)

components is reduced in the transponder due to its operation at a 50-Gbaud symbol rate. When this approach is taken a step further, then POLMUX-RZ-DQPSK modulation with only a ~25-Gbaud symbol rate enables 100-Gb/s transmission. This increases the tolerance to CD and PMD and will allow next-generation optical transmission systems to have a spectral efficiency of 2.0-b/s/Hz.

1.4 OPTICAL MODULATION SCHEMES

There exist a wide variety of modulation schemes which can be chosen to design digital optical communication links. The electric field of the optical carrier is given by [11]:

$$E(t) = \hat{e}Ae^{-j(\omega t+\phi)} \tag{1}$$

where A is the amplitude of the optical field, ω is the optical angular frequency, ϕ is the optical phase and $\hat{e}$ is the polarization vector of the laser source. Each of these four properties of an optical signal defined by these parameters can be modulated by an electrical binary baseband signal q(t) [11]:

$$q(t) = \sum_{i=-\infty}^{\infty} I_i \, q(t - iT_b) \tag{2}$$

with the baseband pulse shape q(t) which is delayed by multiples of T_b, bit period and i^{th} information coefficient where I ϵ [0, 1]. The modulation is mainly differentiated as: Amplitude Shift Keying (ASK), Phase Shift keying (PSK), Frequency Shift Keying (FSK) or Polarization Shift Keying (PolSK), depending on which parameter is to be modulated. Figure 1.1 shows the generation of ASK, PSK and FSK respectively using an electrical binary data stream "01010011". In this work, we focus primarily on some of the optical modulation schemes depending on the modulating parameters.

1.4.1 Intensity Modulation

The most common used modulation format that is currently available today in the deployed optical transmission systems is the Binary Intensity Modulation (IM) or also called ASK. This modulation technique is well known from classical telecommunication theory [12, 13].

a. On-off keying (OOK)

NRZ-OOK has been the choice for modulation scheme for most of the commercial applications from the first application of optical fibers in the middle of the 1970's until only recently. It encodes the information present in the amplitude of the optical field, thus it is an amplitude modulation format. Figure 1.2 depicts the transmitter and receiver structure of NRZ-OOK modulation.

NRZ-OOK is realized by switching of a laser, ON or OFF, which depends on the information to be transmitted at the transmitter side. External modulators as well as direct modulation can be used for NRZ-OOK modulation. Whereas external modulation with a Mach-Zehnder Modulator (MZM) is generally preferred for reduction of the residual chirp

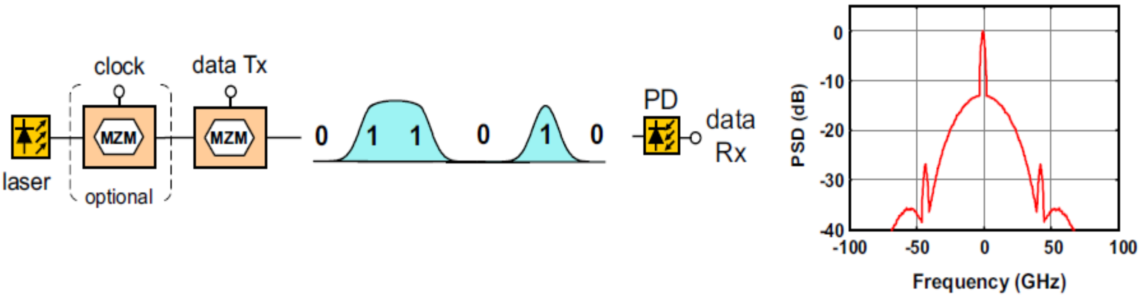


Figure 1.2 NRZ-OOK transmitter and receiver structure with simulated optical spectrum for 42.8-Gb/s NRZ-OOK.

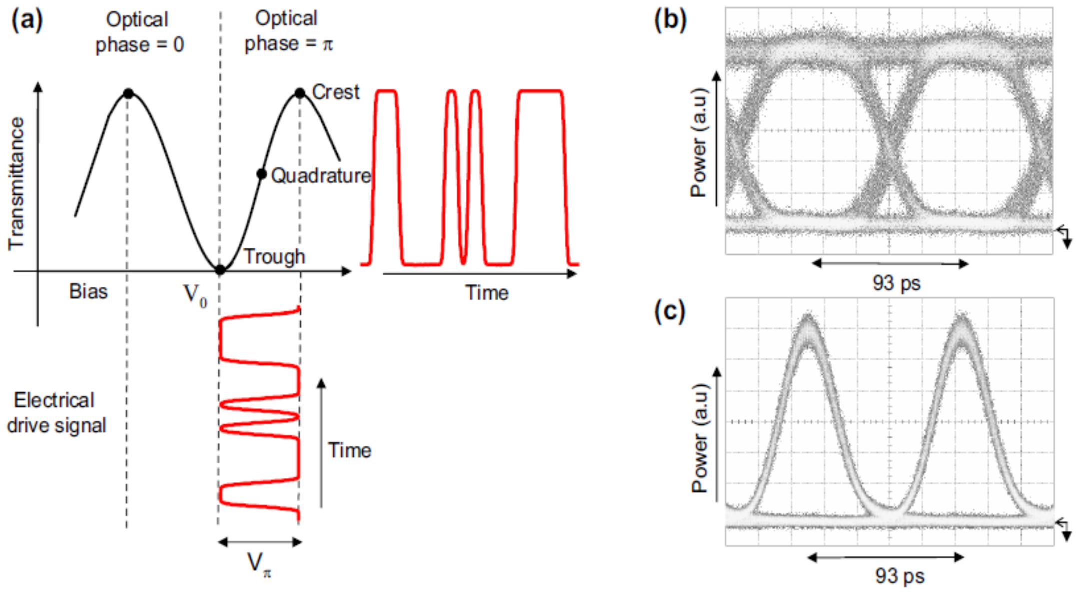


Figure 1.3 (a) Operation of the MZM for OOK modulation and eye diagrams showing, (b) 10.7-Gb/s NRZ-OOK and (c) 10.7-Gb/s RZ-OOK modulation, respectively.

in the modulated signal in case of long-haul transmissions. The output of a laser is modulated by a MZM, typically a Distributed Feedback Laser (DFB), as it results in a chirp-free signal. Figure 1.2 also depicts the optical spectrum of a NRZ-OOK modulated signal. It represents the Power Spectral Density (PSD) as function of optical frequency. The spectrum of NRZ-OOK contains half the optical power at the carrier frequency. There are clock tones spaced at multiples of the symbol rate, but these are strongly reduced in contrast to the carrier component. The optical spectrum has a bandwidth of approximately twice the symbol rate.

Figure 1.3 (a) depicts the operation of a MZM for NRZ-OOK format. The MZM is driven from minimum to maximum transmittance by biasing in the quadrature point. Therefore a peak to- peak amplitude of $V\pi$ is required by the electrical drive signal. Suppression of ripples and overshoots on the electrical drive is possible during modulation due to the nonlinear transmission function of the MZM.

The simple transmitter and receiver structure of OOK modulation comes at the cost of suboptimal transmission properties. The tolerance to non-linear impairments is low because of the strong optical carrier present in OOK modulation. But it can be improved through RZ pulse carving, thus resulting in RZ-OOK modulation [14]. OOK is referred to as NRZ-OOK without RZ pulse carving, which is often abbreviated as NRZ. For WDM transmission, the most suitable RZ-OOK modulation format is Carrier-suppressed RZ (CSRZ). There is a phase change of 180^0 between consecutive symbols of CSRZ due to RZ pulse carving. The optical field has a positive sign for half the ’1’ symbols, while a negative sign for the other half due to this alternating phase change. This gives a zero-mean optical field envelope due to which the carrier component is suppressed. It also improves the nonlinear tolerance in the pseudo-linear system where there is strong pulse overlapping.

Chirped RZ-OOK modulation is another approach to improve the nonlinear tolerance which is also known as CRZ. A specific amount of phase modulation is imposed in CRZ onto the RZ-OOK signal [15, 16]. It can be generated by using a Phase Modulator (PM) for modulating the phase of the RZ-OOK signal. Thus, three modulators in cascade are required, for data coding, pulse carving and phase modulation, respectively. CRZ has an increased nonlinear tolerance compared to RZ-OOK modulation but on the other hand, the signal chirp results in spectral broadening. So there is a trade-off between nonlinear tolerance and spectral efficiency for CRZ. Hence, it is used in ultra long-haul (transoceanic) transmission systems because of its higher nonlinear tolerance.

b. Duobinary

Duobinary modulation is the best example of a class of coding formats called as phase coding formats. Such modulation formats, similar to OOK transmit the information in the amplitude domain and direct detection is used at the receiver side. But there is predefined phase relation between consecutive bits, unlike OOK, that can be used to improve the CD tolerance as well as optical filtering tolerance. It is also sometimes referred to as pseudo binary transmission [17]. A strong correlation between consecutive bits is the main characteristic of duobinary modulation which results in a more compact spectrum. It can be generated either as a 3-level signal that combines both phase and amplitude signalling (’-1’, ’0’, ’1’), which is known as AM-PSK modulation or as a 3-level amplitude signal (’0’, ’0.5’, ’1’). However, the latter case results in a lower receiver sensitivity because the symbol distance is reduced by a factor of two [18]. On the other hand, the use of AM-PSK duobinary generation is advantageous over OOK modulation as it has ideally the same or an even better OSNR requirement. Thus, it can be a useful modulation format in 10.7 Gb/s

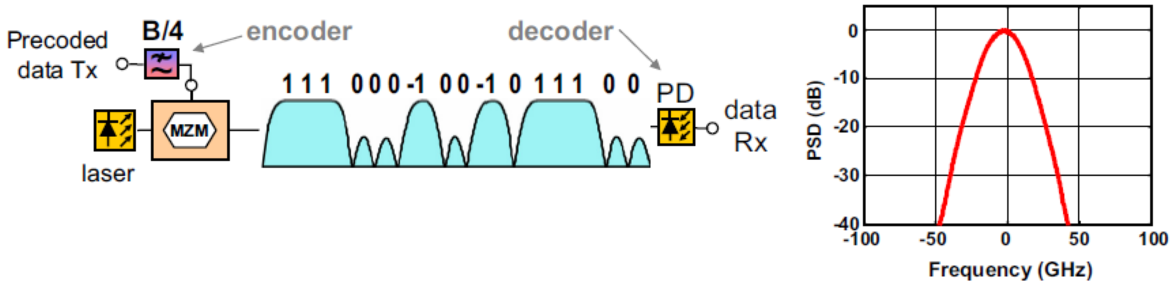


Figure 1.4 Transmitter and receiver structure of duobinary with its optical spectrum at 42.8-Gb/s.

and 42.8-Gb/s optical transmission systems where tolerance to CD is a key design parameter.

Figure 1.4 represents the transmitter and receiver structure of duobinary modulation. The transmitter consists of a standard MZM and for realization of the required correlation between consecutive bits, the electrical signal is encoded before modulation. The logical signal is first pre-coded, prior to encoding such that at the receiver, the transmitted sequence is again recovered. A duobinary pre-coder can be implemented through the operation [18],

$$b(k) = d(k) \oplus b(k-1) \tag{3}$$

where $d(k)$ represents bit k of the input sequence, $b(k)$ is the sequence after pre-coding and $\oplus$ is a logic exclusive OR operation. The pre-coder implementation is therefore a recursive operation, which is difficult to realize with high-speed electronics.

The phase coding in duobinary modulation is exemplified in Figure 1.5. A logical ‘1’ is encoded as either ‘-1’ or ‘1’and a logical ‘0’ is encoded as a zero. When logical ‘1’s are separated by an odd number of logical ‘0’s, then the consecutive logical ‘1’s have a phase shift of 180^0. The duobinary signal constellation in Figure 1.5 depicts the binary logical

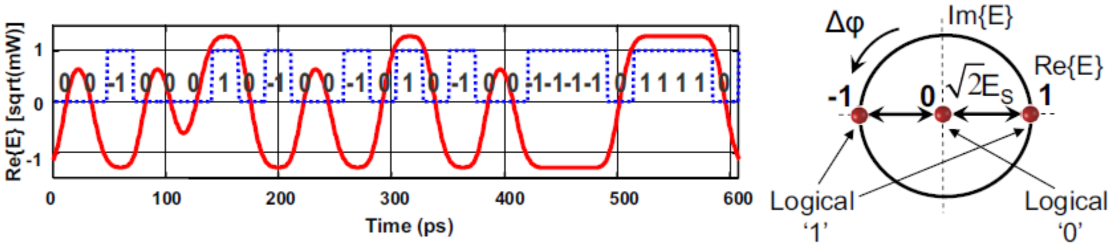


Figure 1.5 Duobinary signal and signal constellation.

symbols represented by three constellation points. Duobinary encoding can be realized through a delay-and-add [18],

$$c(k) = b(k) + b(k-1) \tag{4}$$

where $c(k)$ is the output sequence of the encoder which is used for modulation to convert a binary signal into a 3-level amplitude signal. The electrical driving voltage should have a peak-to-peak voltage of $2V\pi$ in order to realize duobinary modulation with a MZM and the MZM has to be biased in the trough point. The MZM then switches between two crest points, that have a phase difference of 180^0. This effectively maps:

$$0 \rightarrow exp(j \cdot \pi) = -1,$$
$$1 \rightarrow 0 = 0,$$
$$2 \rightarrow exp(j \cdot 0) = 1$$

which is equal to the duobinary partial response code. However, to improve the dispersion tolerance of this code, the spectral width needs to be reduced by electrically low-pass filtering the signal with a bandwidth of $B_0 / 2$, where B_0 is the bandwidth which is twice the inverse of the symbol period ($B_0 = 1 / T_0$). But low-pass filtering with a $B_0 / 2$, bandwidth results in severe eye closing.

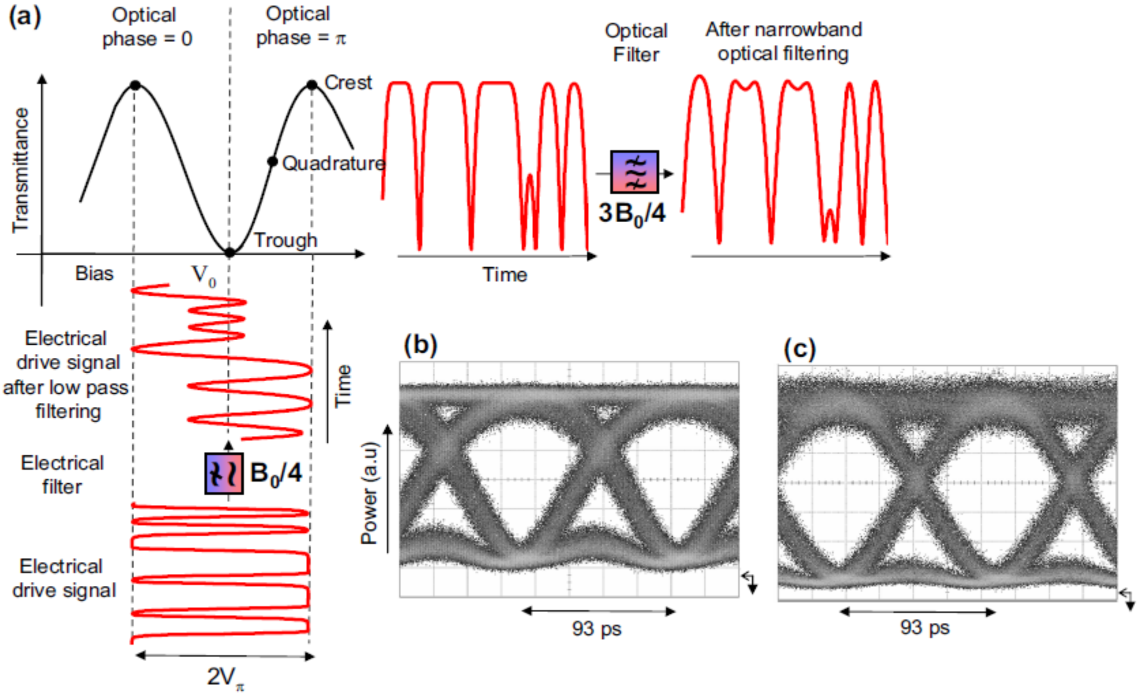


Figure 1.6 (a) Duobinary modulation operation of the MZM and (b-c) eye diagram showing 10.7-Gb/s duobinary (b) without and (c) with additional narrowband optical filtering.

Figure 1.6 (a) depicts duobinary modulation with a MZM preceded by an electrical low-pass filter and Figure 1.6b shows the eye diagram for 10.7-Gb/s duobinary modulation. Narrowband optical filtering filters out more noise at the receiver than a broad de-multiplexing filter, thus resulting in an OSNR improvement of ~4 dB [19]. The filtered duobinary has approximately 1 dB better OSNR tolerance than NRZ-OOK due to narrower optical bandwidth. There are a large number of other partial response codes besides duobinary modulation that offer similar properties [20]. But still duobinary is the most widely used partial response format because of its simple encoding through electrical low-pass filtering. Higher-level partial response (polybinary) codes usually do not offer a further improvement in the dispersion tolerance. Hence the total spectral width cannot be further reduced than the duobinary signals [21].

1.4.2 Phase Modulation

The amplitude of a Digital signal is represented by non-continuous optical power levels in optical intensity modulation. When the phase of a digital signal is denoted by an optical carrier, it is known as an optical PSK.

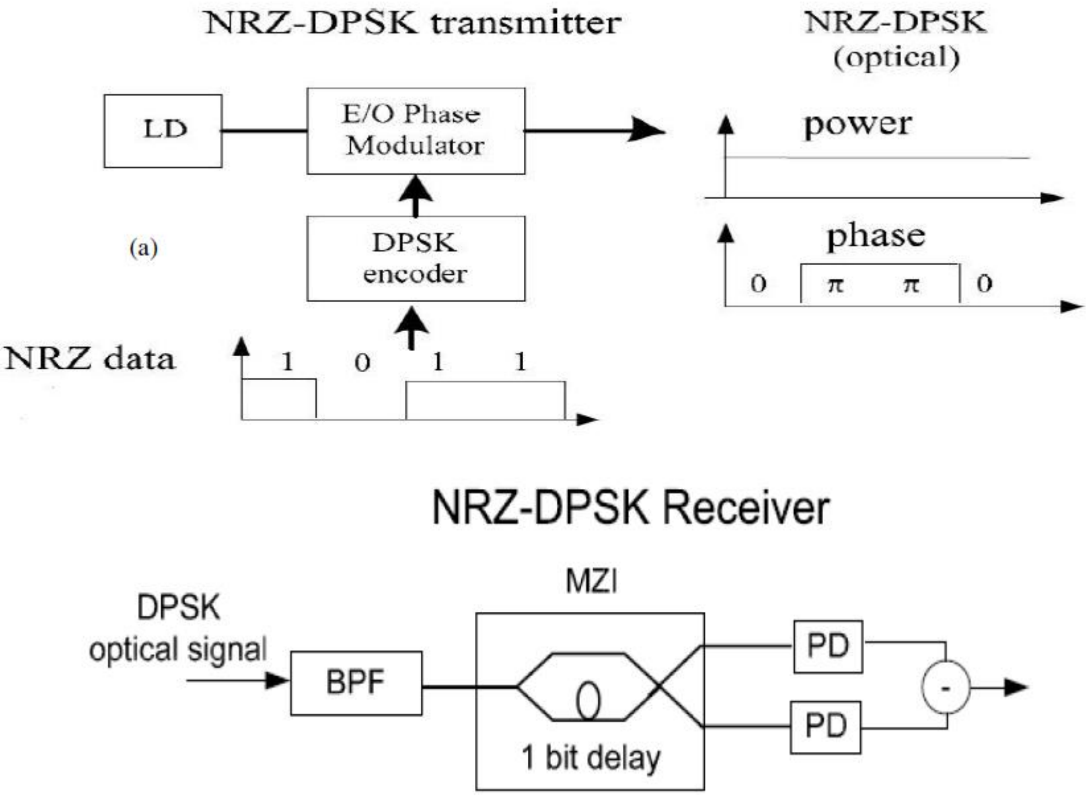


Figure 1.7 Block diagrams of NRZ-DPSK (a) Transmitter and (b) balanced receiver.

a. Differential Phase Shift Keying (DPSK)

The application of active optical phase-locking and recent advancements of single-frequency laser sources make this format viable in practical optical systems. In particular, DPSK is the most often used format [22]. The block diagram of a typical NRZ-DPSK transmitter is shown in Figure 1.7 (a). In a DPSK transmitter, to avoid proliferation of error at the receiver due to differential decoding, the differential encoding is done. In a DPSK encoder, NRZ data is delayed by one bit which is added to the NRZ data by the XOR gate. To generate a DPSK optical signal, this encoded DPSK signal drives an MZM or a PM. A phase change of π between the successive data bits in the optical carrier is used to represent a digital '1' whereas digital '0' is given by no change in phase between the successive data bits. The intensity of the signal is always the same in NRZ-DPSK.

A DPSK optical receiver generally consists of a one-bit-delay Mach-Zehnder Interferometer (MZI) as shown in Figure 1.7(b). MZI is used to convert the phase-to-intensity by correlating each bit with its neighbour. MZI has two outputs which are called Constructive Port (CI) or Destructive Port (DI) respectively. The two consecutive bits are added constructively in the MZI when in-phase at constructive port that results in a high signal level. Whereas, they cancel each other in the MZI when there is a difference of π in the phase of two bits that results in a low signal level.

Both constructive port and destructive port of MZI are used in a practical DPSK receiver, which is known as a balanced receiver. The major benefit of using DPSK than OOK comes from the improvement in the receiver sensitivity by 3-dB which is because of the increase in symbol spacing for DPSK by a factor of 2 for fixed average optical power in comparison to OOK. Also, there is a 3-dB reduction in OSNR for DPSK than OOK for equal Bit Error Rate (BER) due to increased symbol distance which allows DPSK to accept 2 larger standard deviation of the optical field noise. Direct detection can also be applied for the detection of DPSK signals by using one of the MZ-DI port (Figure 1.8).

The performance of NRZ-DPSK is less susceptible by nonlinear effect such as SPM and XPM which are related to modulation of optical power due to constant optical power. However, this is not entirely true when the chromatic dispersion is being considered. Group Velocity Dispersion (GVD) can be used to convert phase modulations into IM and then SPM and XPM can give some distortion in the waveform. In addition, phase noise produced

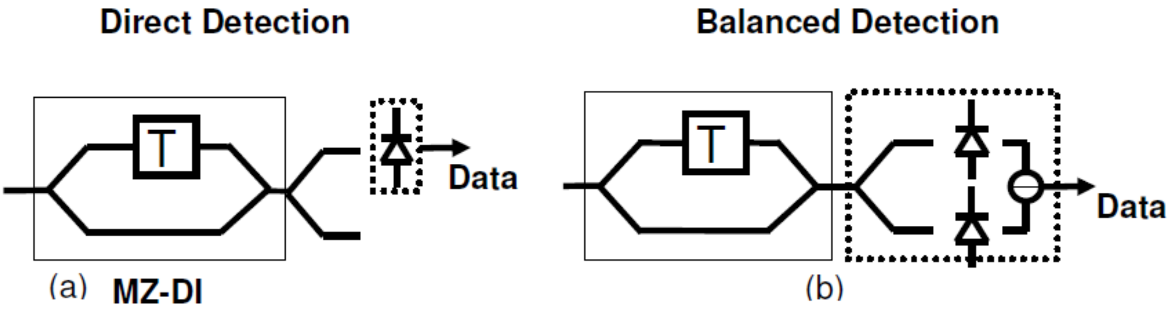


Figure 1.8 DPSK receiver (a) direct detection and (b) balanced receiver

due to non-linearities in the fiber is usually the limiting factor in a long distance DPSK system with optical amplifiers [23].

RZ-DPSK is a strong candidate in order to achieve a longer transmission distance and improved system tolerance to nonlinear distortion. Identical to NRZ-DPSK modulation format, the binary data is encoded as either a ‘0’ or a ‘π’ phase shift between adjacent bits. The width of the optical pulse is narrower than the bit slot due to RZ pulse shape. Typically, there is an addition of an extra modulator which is cascaded with NRZ transmitter to carve NRZ pulses to RZ as shown in Figure 1.9.

Because of additional bit-synchronized intensity modulation in RZ-DPSK, it is also referred to as IM-DPSK. Unlike NRZ-DPSK, in this modulation format, optical power of the signal is no longer constant, so has greater sensitivity to power-related nonlinearity like

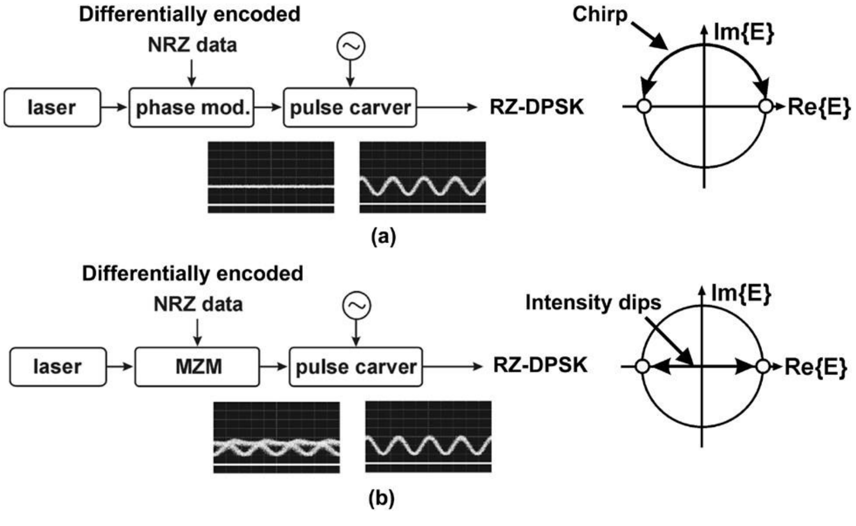


Figure 1.9 Two typical RZ- DPSK transmitters (a) Implementation with phase modulator. (b) Implementation with Mach-Zehnder modulator.

SPM. The optical spectrum of RZ-DPSK is broader than a conventional NRZ-DPSK due to the narrow optical signal pulse width. With optimal dispersion compensation, RZ-DPSK is more tolerant to data pattern dependent SPM-GVD effect because of its regular RZ waveform.

b. Differential Quadrature Phase Shift Keying (DQPSK)

DQPSK is one of the interesting advanced modulation formats that has received good attention lately in the research field of optical communication and is seen as an optimal modulation format for long haul optical transmission at high bit rates [24, 25, 26, 27, 28]. It is used to transmit four phase shifts {0, + π/2, -π/2, π} at a symbol rate of half the total bit-rate. Similar to DPSK, the implementation of a DQPSK transmitter can be done by two parallel MZMs that are operated as PMs.

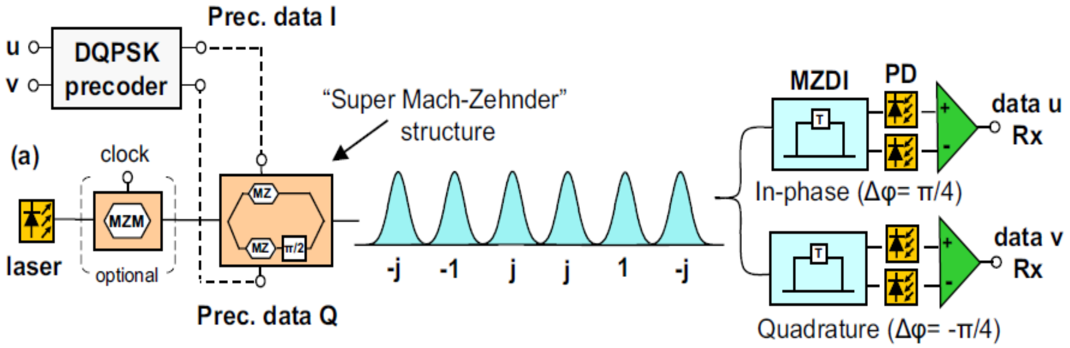


Figure 1.10 Transmitter and receiver structure of DQPSK.

The corresponding transmitter setup is shown in Figure 1.10, consisting of a continuously operating laser source, a splitter which divides the light into two paths of same intensity, two MZMs that operate as phase modulators, an optical π/2 phase shifter present in one of the paths, and then single output signal is produced by a combiner. This transmitter structure provides an advantage of the near perfect π phase shifts which is produced by MZMs, which are independent of drive signal ringing and overshoot. Secondly, only binary electronic drive signals are required by this transmitter structure, which are far easier to generate at high speeds in comparison to multilevel drive waveforms.

Optionally, RZ-DQPSK can be produced by the addition of a pulse carver in the structure. Although the shape of the optical spectrum of DQPSK is quite similar to that of DPSK, but due to the halved symbol rate, the spectrum of DQPSK is compressed in frequency by a factor of two for transmission at fixed bit-rate. High spectral efficiencies can be achieved in WDM systems due to the compressed spectrum and the longer symbol duration makes DQPSK more robust to PMD in contrast to binary modulation formats. One also strives to work with binary electrical signals at the DQPSK receiver, like at the transmitter side, because of the major advantages offered by their implementation in high-speed electronics. Thus, the DQPSK signal is first split into two equal parts, at the receiver side and then the balanced receivers with differently biased delay interferometers (DI) are used in parallel for simultaneously demodulating the two binary data streams contained in the DQPSK signal. The symbol duration for DQPSK demodulation is equal to MZ-DI delay, which is two times the bit duration.

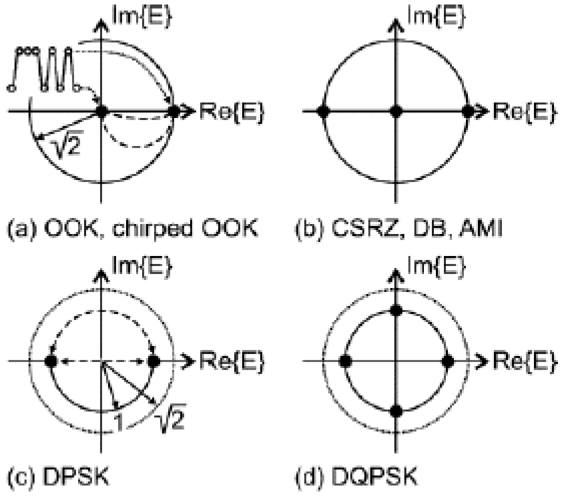


Figure 1.11 Optical symbol diagrams for modulation formats

Figure 1.11 depicts the four significant symbol diagrams consisting of almost all formats encountered in optical communications. These diagrams represent the values of complex optical field given by data symbols which are used either for improving specific format properties or for data transport. All these diagrams are normalized to unity average optical power and are plotted on the same scale. In Figure 1.11 (a), dashed lines represent instances for chirped formats that give transitions between symbols; in Figure 1.11 (c), dashed double-arrows show phase modulator implementations, employing a straight line PM or MZM. Figure 1.11 (b) represents the symbol diagram in CSRZ as well as duobinary and Alternate Mark Inversion (AMI). Figure 1.11 (c) and 1.11 (d) show DPSK and DQPSK, respectively.

c. *Quadrature Phase Shift Keying (QPSK)*

The binary modulation formats have a spectral efficiency limited to 1 b/s/Hz/polarization, whereas formats with 2 bits of information per symbol can attain spectral efficiency up to 2 b/s/Hz/polarization using half the symbol rate while maintaining the bit rate. A reduced symbol rate provides several advantages in the field of optical communications in terms of tolerance to CD and PMD. Quadrature Phase-Shift Keying (QPSK) is the most promising among various modulation formats that carry 2 bits of information per symbol because of its superior transmission characteristics [29].

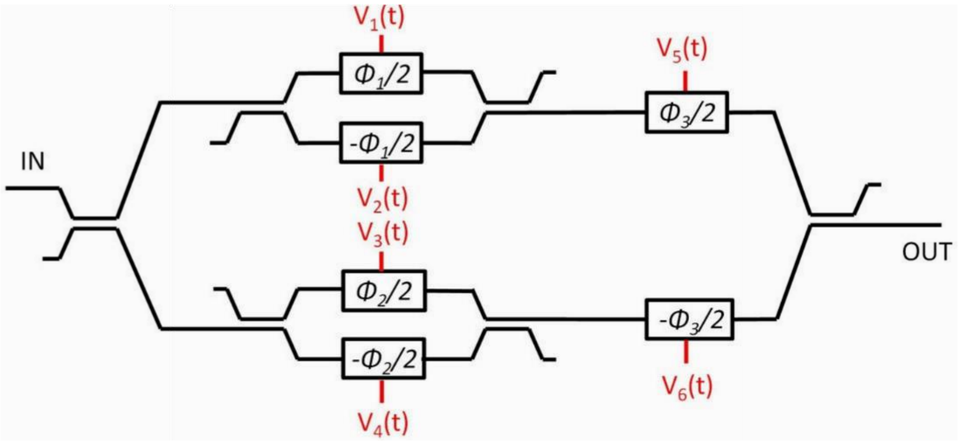


Figure 1.12 Structure of an in-phase and quadrature (I-Q) modulator

A nested structure using three MZMs or a phase modulator can be used to generate a QPSK signal. The latter option has a disadvantage of converting phase noise into intensity noise but on the other side, it only requires one modulator and is cheap to implement. Most of the QPSK transmitters employ nested structure with 3 modulators because of the drawback of using PM. Voltages $V_1(t)$, $V_2(t)$, $V_3(t)$ and $V_4(t)$ are adjusted in the nested structure (Figure 1.12) to have a phase difference of π in the two arms of the inner MZMs and thus, generate two Binary Phase Shift Keying (BPSK) signals. The two BPSK signals are shifted by π/2 with respect to each other within the outer MZM by changing the voltages $V_5(t)$ and $V_6(t)$. A QPSK signal is produced because of the interference between the two BPSK signals which have a phase difference of π/2, as shown in Figure 1.13. During the interference the two BPSK signals shown in red and blue disappear to yield QPSK symbols (shown in black).

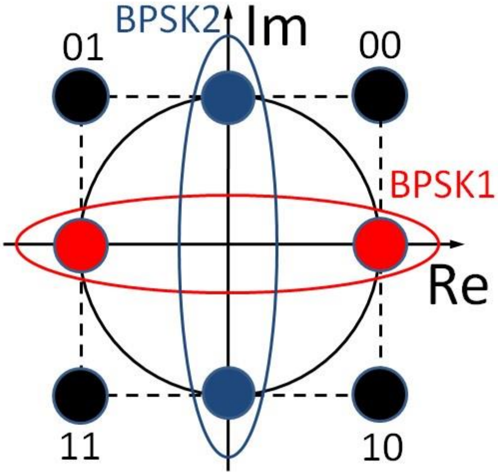


Figure 1.13 QPSK signal generation concept.

Each symbol in a QPSK signal can transmit two bits of information as it can attain any one of the phase values [0, π/2, π, 3π/4] at a particular instant of time. In case of adjacent quadrants, the transition is analogous to the variation in state of only one MZM, whereas in case of opposite quadrants, the transition is similar when both MZMs change their states, hence the symbols of QPSK are inherently Gray coded (e.g. the consecutive symbols differ by only one bit). The Gray coding is required to reduce the BER whenever there is an occurrence of an error in any symbol. In case of non-Gray coded signals, the BER becomes twice than that of QPSK.

1.4.3 Polarization Modulation

So far, we have limited the discussion to modulation formats that employ either the amplitude or phase dimension to transmit information. A different approach towards multi-level modulation formats is the use of the polarization dimension of the optical signal. In comparison to the extensive use of amplitude or PSK in fiber-optic research, modulation using the polarization dimension has attracted only modest attention. This is mainly due to the fact that such modulation formats require a polarization sensitive receiver. POLMUX transmission, sometimes also referred to as Polarization Division Multiplexing (PDM), is the most widely used polarization-sensitive modulation format. It transmits two independent tributaries in each of the orthogonal polarizations and can therefore be used to double the spectral efficiency in comparison to single polarization modulation. In addition, POLMUX signalling reduces the symbol rate by a factor of two when compared with binary modulation formats at the same total bit rate. This can be useful to increase both linear and nonlinear transmission tolerances.

Due to the random birefringence in optical fibers, a polarization sensitive receiver requires polarization de-multiplexing at the receiver. This can be realized either in the optical or electrical domain. POLMUX signalling transfers the information in the polarization of the optical signal, so it is more sensitive to polarization related impairments. In particular, optical polarization de-multiplexing reduces the PMD tolerance, which makes this a key issue to consider. POLMUX signalling has been used in a number of record-capacity breaking laboratory experiments [30, 31] and field trails [32]. However, such record-capacity breaking experiments are generally limited to comparably short transmission distances. This is in part due to the sensitivity of POLMUX to PMD-related impairments in long-haul transmission systems.

a. *Polarization Multiplexed Quadrature Phase Shift Keying (POLMUX)*

PDM is a physical layer method for multiplexing signals carried on electromagnetic waves using the polarization of the electromagnetic waves to distinguish between the different orthogonal signals. Polarization multiplexing can be combined with different intensity modulated and phase modulated schemes to increase spectral efficiency. An example of such kind is POLMUX QPSK which exploits both optical phase and polarization properties of an optical signal. It necessitates four MZMs - one for each orthogonal dimension as shown in Figure 1.14. Each MZM impinges the input electrical signal on one polarization state and in-phase to the transmitter laser signal (optical carrier).

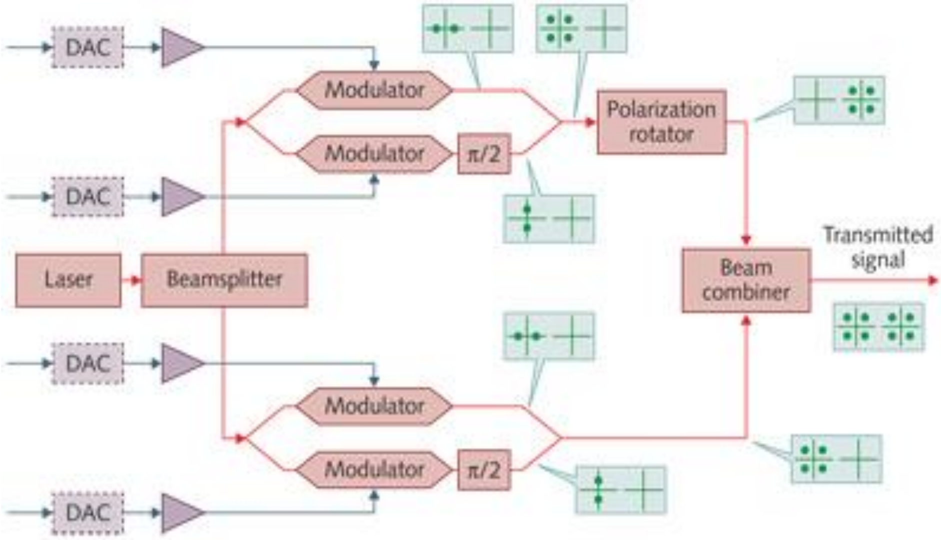


Figure 1.14 A schematic shows a POLMUX in-phase/quadrature (I-Q) optical transmitter.

For modulation formats with higher spectral efficiency than POLMUX QPSK, Digital-to-Analog Converters (DACs) are also needed to aggregate multiple electrical binary signals prior to optical modulation.

Optical phase and polarization can only be defined with respect to a reference optical signal. Therefore, deciphering high-order modulation formats requires mixing the received signal with an optical Local Oscillator (LO) in a coherent receiver as depicted in Figure 1.15 along with received constellation diagrams in Figure 1.16. In addition, coherent detection results in a linear transfer function between the received optical field and the electrical output. This allows improvement in linear fiber propagation impairments such as CD and PMD in the electronic domain using ultrafast Analog-to-Digital Converters (ADCs) integrated with Digital Signal-Processing (DSP) chips [33]. Hence, POLMUX QPSK has the great advantage of mitigating the problems of increasing both the electrical analog amplification bandwidth and the digital signal processing speed because it can reduce the symbol rate to 1/4 of the data transmission rate. A summarized table showing some of the optical modulation schemes with their optical modulator and receiver configurations is shown in Figure 1.17.

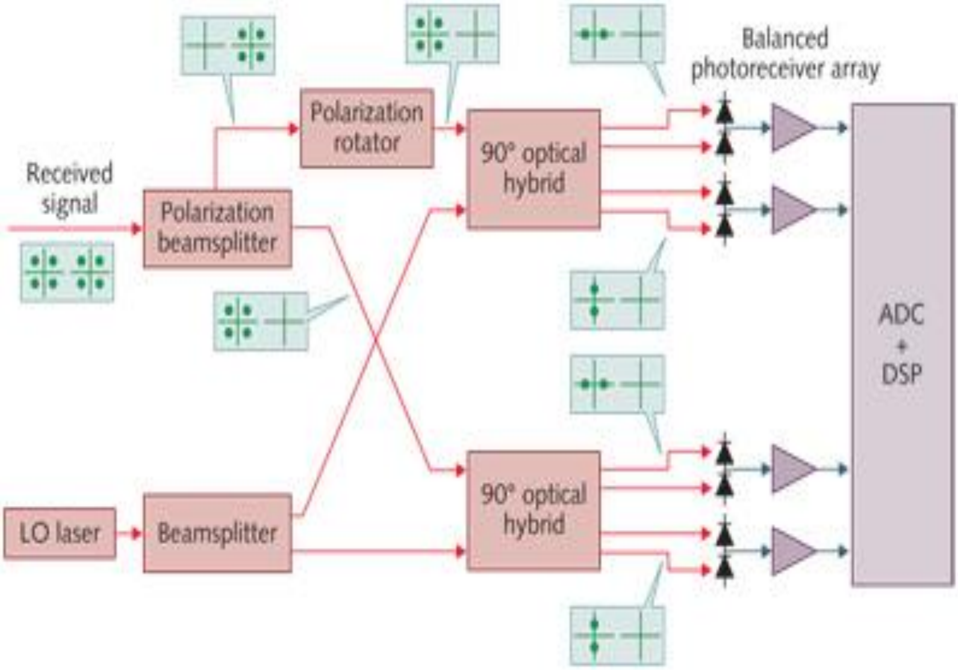


Figure 1.15 A schematic of a coherent dual-polarization I-Q optical receiver.

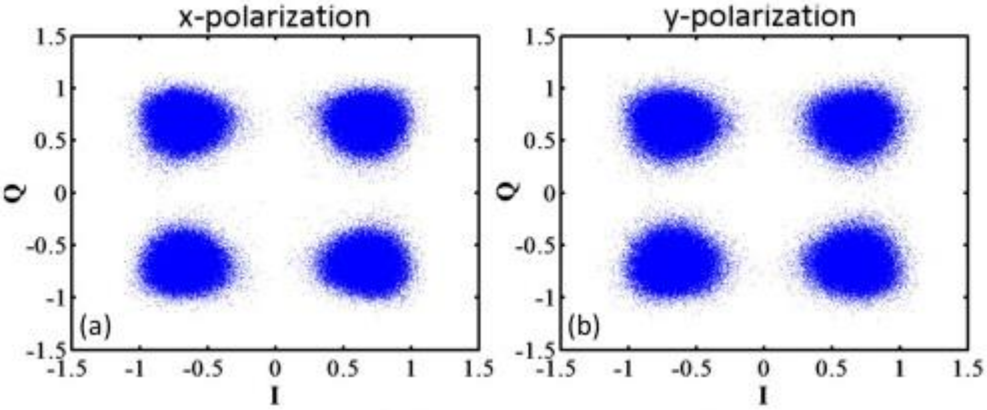
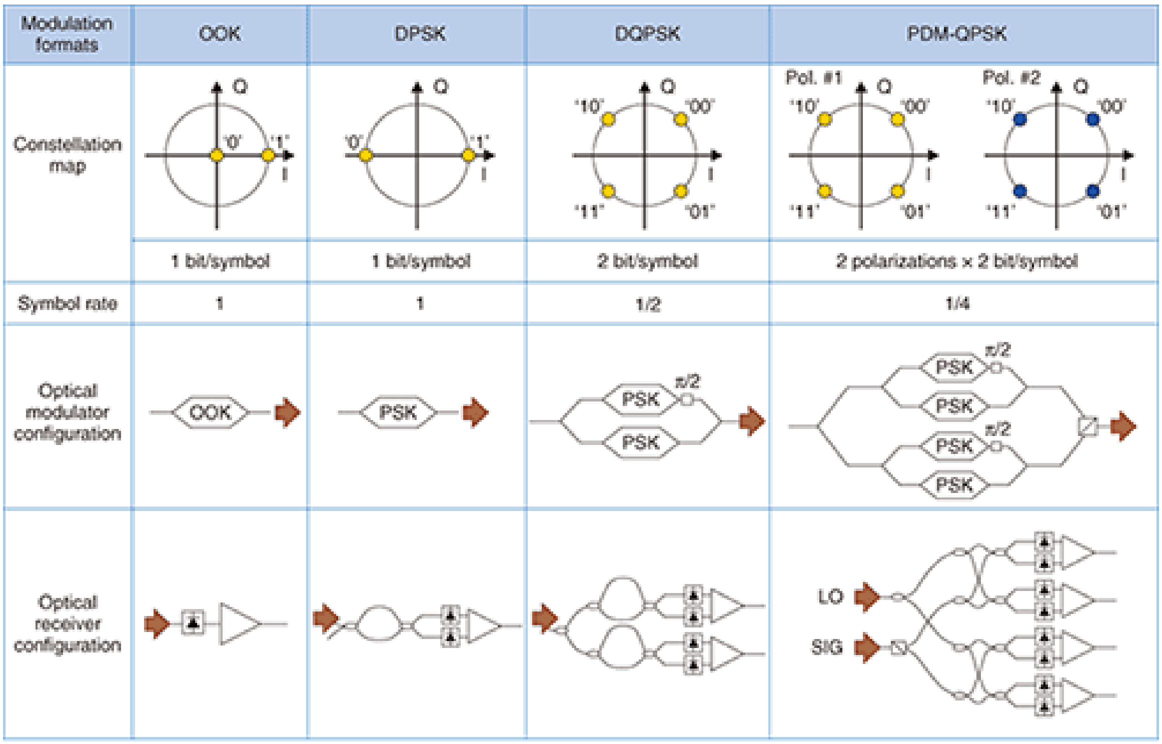


Figure 1.16 POLMUX QPSK constellation diagram.



Modulation formats	OOK	DPSK	DQPSK	PDM-QPSK
Constellation map	1 bit/symbol	1 bit/symbol	2 bit/symbol	2 polarizations × 2 bit/symbol
Symbol rate	1	1	1/2	1/4
Optical modulator configuration				
Optical receiver configuration				

LO: local oscillator light
Pol.: polarization
SIG: signal light

Figure 1.17 Some optical modulation schemes with their optical modulator and receiver configurations.

1.5 OBJECTIVE OF DISSERTATION

1. To compare different optical data modulation schemes at different data rates.
2. To compare the performance of transmission of 112 Gb/s dual carrier POLMUX NRZ-DQPSK with that of dual carrier POLMUX RZ-DQPSK systems with respect to changes in state of polarization.
3. To investigate the transmission performance of 112 Gb/s POLMUX QPSK signal in OOK/DPSK WDM system.

1.6 ORGANISATION OF DISSERTATION

Chapter 2 gives literature survey about the topic of the dissertation. In order to start the dissertation, the first step is to study the papers that have been already published by other researchers. Paper related to this work are chosen and studied. With the help of literature review, it becomes easier to perform this work.

Chapter 3 describes the simulation behaviour of different optical modulation schemes with increase in data rate. These formats are also compared with each other, particularly at high bit rates.

Chapter 4 includes the analysis of the transmission of 112 Gb/s dual carrier POLMUX DQPSK system when the state of polarization of the signal is varied. It also explains the difference between POLMUX NRZ-DQPSK and POLMUX RZ-DQPSK system at 112 Gb/s.

Chapter 5 is devoted to the investigation of transmission of 112 Gb/s POLMUX QPSK signal in a WDM system comprising of OOK or DPSK channels. It discusses the impact of XPM and Cross-Polarization Modulation (XpolM) on the transmission system.

Chapter 6 summarizes the thesis and suggests future research directions in this area.

CHAPTER 2

LITERATURE SURVEY

The research in the field of the optical fiber communication has seen a lot of progress in the past few years since it has become the backbone of the communication network in the society. With tremendous increase in data rate from 10 Gb/s to 40 Gb/s or higher bit rates, there is a requirement to opt for an appropriate optical modulation scheme that can satisfy the increase in demand of capacity. Many studies have been done till now to look for the requisite optical modulation format. This chapter includes the research papers that were studied in order to obtain the objectives listed in the dissertation. They are categorised on the basis of modulation formats.

2.1 INTENSITY MODULATED

Rene Schmogrow et al. [34] established theoretical results as well as used numerical simulations to develop a relation between Error Vector Magnitude (EVM), OSNR and BER. Six complex modulation formats have been generated sequentially at symbol rates of 20 Gbaud and 25 Gbaud at 1550 nm and the modulated carrier has been combined with variable noise source so that the OSNR of the system can be varied. It has been concluded that instead of Q-factor evaluation for OOK systems, EVM can be used as a quality measurement parameter for reliable estimation of BER for advanced modulation formats in coherent optical transmission systems.

2.2 PHASE MODULATED

Nimal Ekanayake et al. [35] investigated the performance of transmission of M-ary coherent PSK and DPSK in the presence of Non-linear Phase (NLP) noise and ASE noise in a long optical fiber link. The effects due to CD or any other distortion have not been considered. The two cases have been considered of dependent NLP and ASE noises, and independent NLP and ASE noises and expressions for Symbol Error Probability (SEP) have been derived. The applicability of the SEP expressions have been demonstrated for 2-, 4-, 8- and 16-level signalling. The results showed that the SEP is very much different for the case of independent phase noise, comparative to the case of dependent phase noise for all M’s. Whereas the DPSK system has almost the same SEP, except for M=2.

Mats Skold et al. [36] presented a way to use non-linear optical sampling techniques, such as four wave mixing based sampling, for the signal characterization of systems employing advanced modulation formats. The experiments were conducted with NRZ-DPSK data at 42.6 Gb/s and RZ-DPSK at 170.4 Gb/s which gave sub-picosecond resolution for balanced detected signals. Also, clear eye diagrams with temporal resolution of 0.8 ps were obtained due to high SNR and low timing jitter. For the case of high-speed optical signals, amplitude and phase characterization was demonstrated by a coherent measurement tool, presented by asynchronous sampled constellation diagrams. It was concluded that the concept of real-time sampling could be used with signals of polarization diversity for the measurement of their bit error rates.

Radan Slavík et al. [37] presented a method to mitigate noise that was generated during transmission of phase encoded signals which was to employ phase sensitive amplifiers that can be used to remove amplitude as well as phase noise from phase-encoded signals. A signal regenerator based on phase sensitive amplifiers that used degenerate FWM was implemented in a network that only had noisy signal present at the device input. Multicasting and simultaneous wavelength conversions were performed by the developed regenerator. This regenerator was able to cope up with 40 ps/nm of residual dispersion for a 40 Gb/s DPSK signal, that provided advantages in performance in comparison to a fully compensated link without using the regenerator. The theoretical analysis suggested that the limit to the chromatic dispersion tolerance was set by the overlapping of consecutive bits.

S. Chandrasekhar and X. Liu [38] studied the impact of XPM on RZ-DQPSK from nearby OOK channels in the experimental demonstration of dense WDM transmission system of 42.7 Gb/s RZ-DQPSK having 10.27 Gb/s NRZ-OOK channels. Different degrees of penalties have been imposed on DQPSK channels, which depend on dispersion map and channel plan because of XPM from the OOK channels. The two nearest neighbouring 10.7 Gb/s OOK channels which are 50 GHz away mostly limits the performance of 42.7 Gb/s RZ-DQPSK due to XPM. XPM penalty have been found out to be strongly dependent on residual dispersion per span and channel occupancy. The ways to reduce XPM penalty has been suggested which include the introduction of guard band between OOK and RZ-DQPSK channels at the cost of reduced system capacity or the introduction of large dispersion excursion. There has been an improvement in the transmission performance of the system with increase in residual dispersion per span as it helps in the mitigation of XPM penalty.

Avishek Nag et al. [39] proposed a new optical networking design with mixed line rates using transceivers with different optical modulation formats. They suggested that in order to meet the requirements of future telecom networks, setting up of different lightpaths at different bit rates in optical WDM systems in the backbone telecom mesh would be a cost effective method as line rate decides the reach of a lightpath (without regeneration). So there would be a trade-off between transparent reach and capacity of a lightpath by assignment of a line rate. The need for signal regeneration can be minimized on the basis of this assignment and signal-quality constraints. Also, the employment of advanced modulation formats can relax the constraint on transparent reach. The results showed that there has been an overall network cost reduction when the extended reach and volume discount of 100 Gb/s DQPSK with mixed line rates were combined.

Zhaohui Li et al. [40] demonstrated WDM transmission of mixed systems comprising of 100 Gb/s CS-RZ DQPSK signals surrounded by 40 Gb/s CS-RZ duobinary signals with adjacent channel spacing of 200 GHz. The effects of linear and non-linear cross talk between the neighbouring channels were evaluated. After transmission of 1500 km of SSMF, BER of e^{-3} for CS-RZ DQPSK and BER of $5e^{-4}$ for CS-RZ duobinary signals could be achieved in a hybrid system of 8-channel 100 Gb/s CS-RZ DQPSK and 8-channel 40 Gb/s DRZ signals with launch power of 2 dBm of each CS-RZ duobinary signal. The greater BER of CS-RZ DQPSK has resulted from non-linear effects such as cross-phase modulation from CS-RZ duobinary to DQPSK signals in WDM systems.

Guo-Wei Lu et al. [41] demonstrated a format conversion scheme from 120 Gb/s RZ-D8PSK to 80 Gb/s RZ-DQPSK. The proposed scheme could be applied to the signal implementing Trellis coded modulation by erasing its redundant overhead tributary which can be achieved in a non-linear fiber through FWM. The converted DQPSK has an 8-dB sensitivity improvement in comparison to the input D8PSK signal. This improvement is very much useful in inter-connecting neighbouring networks which deploy different modulation formats.

Linghao Cheng et al. [42] demonstrated the monitoring scheme for chromatic dispersion on the basis of average variance of optical power for advanced modulation formats, such as Quadrature Amplitude Modulation (QAM) and PSK, by both simulations and experiments. The simulations does not included optical noise so that chromatic dispersion is the only reason for variance in the optical power. The calculations and experiments were performed on 25.6 Gb/s QPSK with Gaussian pulses. The results showed that the calculation of variance of received optical power can be effective method for the measurement of waveform distortion due to CD in a transmission link. But for dispersion values lower than 850 ps/m, the measurement is highly dependent on pulse shape which may make CD monitoring unreliable.

Amirhossein Ghazisaeidi and Leslie Ann Rusch [43] proposed a Digital Filter-based Back-propagation (DFBP) scheme for post compensating the non-linear effects induced by Semiconductor Optical Amplifiers (SOA) in coherent receivers of advanced modulation formats. The overall post-compensation performance of the proposed scheme has been compared with the fourth order Runge-Kutta method and it has been found that the former is less complex as well as more accurate than the latter, in terms of root mean square residual distortion for realistic situations. The BER performance and the impact of SOA saturation level on 16-QAM has been examined. For moderate SOA saturation levels, DFBP is found to be more efficient and for 16-QAM using SOA and DFBP compensation, the system reach can be increased by 40 km. The results showed that when the back-propagation stages in DFBP are increased to 10, then post-compensated BER performance always remain below FEC threshold for 10% tolerance in the characteristics of SOA parameters.

Antonio Napoli et al. [44] proposed the use of DSP along with advanced modulation formats and coherent detection to enable data-rates as high as 400 Gb/s per channel over distances in the order of 1000 km. This has been achieved by the use of digital equalization algorithms which allows to compensate fully for the linear fiber impairments. In order to compensate for the non-linear channel impairments due to Kerr effect by the Digital Back-propagation (DBP), two methods to reduce its hardware complexity have been proposed. The first confirmed and extended the published results for non-dispersion managed link, while the second introduced a novel method that can be applied to dispersion managed links, which showed complexity reductions in the order of 50% and up to 85%, respectively. The proposed techniques were validated by comparing the results that were obtained through post-processing of simulated and experimental data that employed single channel and WDM configurations, with advanced modulation formats, such as QPSK and 16-QAM. The considered net symbol rate for all cases was 25 GSymbol/s. The post-processing results showed that hardware complexity can be significantly reduced without affecting the system performance. Also, a detailed analysis of the obtained reduction was presented for the case of dispersion managed link in terms of number of required complex multiplications per transmitted bit.

2.3 POLARIZATION MODULATED

Giampiero Contestabile et al. [45] investigated experimentally the different modulation formats employing intensity, phase and polarization multiplexing in terms of transparency to FWM in SOAs. Two schemes have been used for wavelength conversion to 40 Gb/s single polarization and 80 Gb/s PM signals for polarization independent signals such as NRZ-OOK and NRZ-DPSK. The results showed that the conversion scheme was transparent to the modulation formats employing intensity and phase but not transparent to polarization dependent signals as non-linear interactions come into play even for 1 dB \residual polarization dependence.

D. van den Borne et al. [46] investigated the performance of multi-level modulation formats to provide optical communication systems with high spectral efficiency. They experimentally demonstrated the WDM transmission of 40 x 85.6 Gb/s POLMUX RZ-DQPSK system over 1700 km on a 50-GHz grid which resulted in a capacity of 3.2 Tb/s with a spectral efficiency of 1.6 b/s/Hz. Despite the high spectral efficiency, the PMD related impairments largely influenced the system. Also, the trade-off between bit-aligned and interleaved POLMUX for RZ-DQPSK has been discussed which showed that in comparison to bit-aligned POLMUX, interleaved POLMUX has less DGD tolerance but more non-linear tolerance.

Valeria Vercesi et al. [47] proposed two implementations for optical multiplexing architecture which are cost-effective. To enable effective utilization of spectrum without the use of electronic data processing, a number of 10 Gb/s OOK signals are multiplexed into a 20 Gb/s or 40 Gb/s dual polarization DQPSK and demultiplexed optically. Also, a new routing strategy has been proposed which takes account the features and constraints of the architecture that reduced the overall blocking probability. Evaluation of the performance of the routing strategy and the proposed architecture has been done in a network area through simulations. The results showed that when the baud rate of the architecture is preserved, then there is small blocking probability when number of multiplexed signals are large as the same amount of spectrum accommodated greater number of traffic requests. The routing strategy maximised the trunk segment so that the overall throughput can be increased.

P. Boffi et al. [48] investigated the performance of 100 Gb/s POLMUX RZ-DQPSK system using direct detection and automatic polarization stabilization by means of a magneto-optic device. The measurement of BER against OSNR has been evaluated experimentally to check CD robustness of the proposed scheme after propagation in 8.8 km Standard Single Mode Fiber (SSMF) in an uncompensated link, in the presence of a polarization scrambler. The results showed that after 100 ps/nm, there is a penalty of 2-dB in the system because of CD and Differential Group Delay (DGD) tolerance of 4 ps. It has been concluded that the long term stability of proposed 25 Gbaud solution offers several advantages in comparison to other schemes such as OOK, DQPSK and duobinary due to its reduced bandwidth and robustness towards CD.

Mohammad S. Alfiad et al. [49] investigated experimentally the effects of dispersion maps on the transmission of 111 Gb/s POLMUX RZ-DQPSK signal in different link structures with four different fibers having varying properties. It has been shown that in the double periodic dispersion map, a Dispersion Managed (DM) link with sufficient large per-span under-compensation can behave similarly to that of a non-DM link as the difference in their performance is because of XPM penalty which can be significantly reduced by increasing the walk-off between neighbouring channels at different spans. When different fibers have been compared, then it has been proved that the family of fibers with low non-linear coefficient, high dispersion coefficient and low loss with a non-DM link can increase the optical transparent reach of such links. It has also been shown when the two polarization tributaries of 111 Gb/s POLMUX RZ-DQPSK are interleaved, there is very little advantage.

Ekawit Tipsuwannakul et al. [50] experimentally compared the performance of 112 Gb/s POLMUX RZ 8-ary PSK (POLMUX-RZ-D8PSK) with that of POLMUX-RZ-DQPSK. The parameters considered are GVD, OSNR requirement and DGD tolerances. The results showed that the OSNR requirement of D8PSK is 5.5 dB higher than that of DQPSK in both single channel and 100-GHz spaced WDM transmission. Whereas in dense WDM systems, the OSNR requirements of both D8PSK and DQPSK are comparable because of compact spectrum of D8PSK. The GVD tolerance of D8PSK has been found out to be higher by 15 ps/nm than DQPSK due to its lower baud rate. Thus POLMUX-RZ-D8PSK showed exceptional performance in DWDM systems but at the expense of higher OSNR requirement and increased transmitter/receiver complexity.

Chris R. S. Fludger et al. [51] presented some experimental results regarding the performance of transmission of POLMUX-RZ-DQPSK at a bit rate of 111 Gb/s. The application of a coherent digital receiver has been discussed for a transmission system which is compatible with future 100 Gb/s Ethernet to compensate the linear transmission impairments and polarization demultiplexing. This type of coherent detection resulted in high tolerance to CD and PMD with subsequent electronic equalization and excellent noise performance. The feasibility of employing 111 Gb/s POLMUX-RZ-DQPSK in a DWDM system with a channel spacing of 50-GHz and spectral efficiency of 2 bits/s/Hz over 2375 km has been shown, owing to these advantages. Also, the impact of digital signal processing and sampling has been discussed with either 1 or 2 samples/bit and the results showed that a large tolerance towards CD can be obtained by combining 1 sample/bit signal processing with low-pass electrical filtering. The proposed modulation and detection techniques have been found to be compatible with the already implemented 10 Gb/s infrastructure.

C. Porzi et al. [52] proposed a novel method for advanced modulation formats for 100 Gb/s coherent systems which provide signal processing. They demonstrated an all-optical selective switching of QPSK signals by exploiting a single SOA, MZI. They simultaneously achieved wavelength conversion of bursts of data when the optical gate control signal was present which enabled dynamic add/drop operations in packet switched networks and multi-channel coherent systems. This further allowed flexibility in resources optimization of the network. The FWM effect and the destructive interference induced by cross-phase modulation in SOA-MZI has been taken into account for all the experiments. A bit error rate below 10^{-3} prior FEC has been observed for dual-channel single polarization, single-channel single polarization and dual channel POLMUX-QPSK signals, by using digital signal processing at the detector side. It has been reported that the maximum penalty in OSNR is below 1.5 dB for POLMUX QPSK whereas for single polarization, it is negligible.

Jérémie Renaudier et al. [53] reported a series of experiments conducted on 28-Gbaud Polarization Switched QPSK (PS-QPSK) siganls for long haul transmission in WDM systems. A novel method for generating and detecting PS-QPSK signals has been proposed which is also compatible with constant modulus algorithm used in the detection of coherent POLMUX-QPSK signals. The performance of PS-QPSK signals has been compared with that of POLMUX-QPSK signals at a bit rate of 100 Gb/s, having the same hardware configuration with minor variations in DSP architecture at the receiver side, in a SSMF over a WDM system. It has been concluded that for dispersion non-managed and dispersion managed transmission links, the PS-QPSK signals have 3-dB higher Q^2-factor performance than POLMUX-QPSK signals. PS-QPSK signals could operate in the transmission links even when the POLMUX-QPSK system fails, but at the cost of reduction in the transmission capacity.

Enrico Torrengo et al. [54] investigated the performance of 112 Gb/s POLMUX-QPSK on the basis of pulse shape in a WDM transmission system consisting of ten channels with a channel spacing of 50-GHz. RZ with 50% duty cycle has been compared with the NRZ format and the former showed better performance in single channel and WDM systems. According to the results, the system reach has been increased from 6560 to 7760 km in case of single-channel and from 5920 to 7360 km in the WDM experiments. Hence, an improvement in the transmission margin of RZ format for both single channel and WDM experiments has been obtained but at the cost of additional circuitry for pulse-carver, increased linear WDM cross-talk, reduced spectral efficiency and other disadvantages associated with the wider spectrum.

Table 2.1: Literature survey categorized according to different optical modulation schemes.

MODULATION SCHEME	AUTHORS	WORK DONE	RESULTS
OOK	Rene Schmogrow et al.	A relationship between EVM, OSNR and BER was established for OOK systems.	EVM can be used as a quality measurement parameter for reliable estimation of BER in place of Q-factor.
PSK and DPSK	Nimal Ekanayake et al.	The performance of transmission of M-ary coherent PSK and DPSK in the presence of NLP noise and ASE noise in a long optical fiber link was investigated.	The DPSK system has almost the same SEP for the both the cases of independent and dependent phase noise for all M's, except for M=2.

DPSK	Radan Slavík et al.	A method to mitigate noise produced during transmission of phase encoded signals using phase sensitive amplifiers was presented.	A regenerator based on phase sensitive amplifiers showed better performance as compared to a fully compensated link without using regenerator for 40 Gb/s DPSK system.
DQPSK	S. Chandrasekhar and X. Liu	The impact of XPM on 42.7 Gb/s RZ-DQPSK from nearby 10.27 Gb/s OOK channels was experimentally demonstrated in a DWDM transmission system.	The use of guard band between OOK and RZ-DQPSK channels showed reduced XPM penalty but at the cost of reduced system capacity or the introduction of large dispersion excursion.
DQPSK	Zhaohui Li et al.	The WDM transmission of mixed systems comprising of 100 Gb/s CS-RZ DQPSK signals surrounded by 40 Gb/s CS-RZ duobinary signals with adjacent channel spacing of 200 GHz was demonstrated.	The BER for CS-RZ DQPSK was found to be e^{-3} and for CS-RZ duobinary signals, it was $5e^{-4}$ in a hybrid system of 8-channel 100 Gb/s CS-RZ DQPSK and 8-channel 40 Gb/s DRZ signals with launch power of 2 dBm of each CS-RZ duobinary signal after transmission of 1500 km of SSMF.
DQPSK	Guo-Wei Lu et al.	A format conversion scheme from 120 Gb/s RZ-D8PSK to 80 Gb/s RZ-DQPSK was demonstrated using FWM.	The converted DQPSK has an 8-dB sensitivity improvement in comparison to the input D8PSK signal.

QAM	Amirhossein Ghazisaeidi and Leslie Ann Rusch	A DFBP scheme for post compensating the non-linear effects induced by SOA in coherent receivers of advanced modulation formats was proposed.	The post-compensated BER performance always remain below FEC threshold for 10% tolerance in the characteristics of SOA parameters when the back-propagation stages in DFBP are increased to 10.
POLMUX DQPSK	D. van den Borne et al.	The WDM transmission of 40 x 85.6 Gb/s POLMUX RZ-DQPSK system over 1700 km on a 50-GHz grid was experimentally demonstrated.	The interleaved POLMUX has less DGD tolerance and more non-linear tolerance as compared to bit-aligned POLMUX.
POLMUX DQPSK	P. Boffi et al.	The performance of 100 Gb/s POLMUX RZ-DQPSK system was investigated using direct detection and automatic polarization stabilization by means of a magneto-optic device.	There is a penalty of 2-dB in the system because of CD and DGD tolerance of 4 ps after 100 ps/nm.
PS-QPSK	Jérémie Renaudier et al.	The performance of PS-QPSK signals was compared to POLMUX-QPSK signals at a bit rate of 100 Gb/s	The PS-QPSK signals have 3-dB higher Q^2-factor performance than POLMUX-QPSK signals for dispersion non-managed and dispersion managed transmission links.

POLMUX QPSK	Enrico Torrengo et al.	The performance of 112 Gb/s POLMUX-QPSK was investigated on the basis of pulse shape in a WDM transmission system consisting of ten channels with a channel spacing of 50-GHz.	The RZ format with 50% duty cycle showed better performance than NRZ format in single channel and WDM systems.

CHAPTER 3

COMPARISON OF DIFFERENT OPTICAL MODULATION SCHEMES

In this chapter, the transmission of different optical data modulation formats, namely, OOK, DPSK, NRZ-DQPSK and RZ-DQPSK, has been discussed. A comparison of their performance at different values of bit rate has been made by means of numerical simulations. It has been observed that at bit rate of 40 Gb/s, for an OSNR requirement of 20 dB, the BER of OOK = 10^{-4}, whereas for RZ-DQPSK, it is 10^{-9}. When the bit rate is increased to 100 Gb/s, there is only an improvement of 0.25 dB in OSNR requirement for RZ-DQPSK than NRZ-DQPSK format. The BER is decreased by 0.01 for RZ-DQPSK format while for OOK format, it is decreased by 0.1 for 1 dB OSNR improvement at bit rate of 100 Gb/s. Thus, RZ-DQPSK shows an appreciable performance at high data rates.

3.1 INTRODUCTION

Over the past few years, Optical fiber communication has become the backbone of the global information infrastructure, owing to its many advantages. The main attractions among them are the larger capacity as compared to copper counterparts and immunity against external disturbances and electromagnetic interference. Due to its high speed data transfer capability and huge bandwidth, it has become today’s dominant technology for the growing demand in broadband traffic, mostly High Definition Television (HDTV) broadcasting services, internet access, video on demand, etc. [55].

Earlier, only one modulation method, that is, OOK was used for the transmission rates of upto 10 Gb/s. Nowadays, to meet the demand for greater capacity in optical communication networks, an increase in transmission speed from 10 Gb/s to 40 Gb/s and beyond is required. But the bandwidth is also quadrupled when the transmission rate is quadrupled to 40 Gb/s, which results in four-fold increase in the noise power level in the communication channel. This eventually reduces the sensitivity of the system. Also, fiber impairments in an optical fiber such as CD, PMD and non-linear effects like FWM, SPM and XPM degrades the transmission signal quality. So the way out of this dilemma is provided by higher-level modulation methods.

Nikolaos Sotiropoulos et al. [56] proposed to use differential multi-level modulation formats with high spectral efficiency in very high-speed Time-Division Multiplexing Passive Optical Networks (TDM-PONs), both by simulations and experimentally. The performance of Differential 8-PSK and incoherent 16-QAM was evaluated and the results showed that incoherent detection can provide a cost-effective solution with increased bit rate.

For achievement of high-speed signal processing functions, Alan E. Willner et al.[57] proposed the combined use of signal process and optical field, that is, optical signal processing – namely, advanced modulation formats, and analog and digital signals. They presented some applications of optical signal processing, including optical correlation, Finite Impulse Response (FIR) filtering, optical Fast Fourier Algorithm (FFT) and Discrete Fourier Transform (DFT) and optical logic. Sub-system applications like multiplexing, wavelength conversion, de-multiplexing and multicasting can be enabled by non-linear photonic interactions.

All the formats after OOK have earned the qualifier of "advance" in optical communication systems. These advanced optical modulation formats have received considerable attention over the past few years. So this research work examines the performance of various optical modulation formats at different bit rates. This chapter is organised as follows. Section 2 gives the theoretical analysis on some of the data modulation formats. Section 3 describes in detail the simulation set-up for the comparison of different formats. Section 4 and section 5 contains the results and conclusion respectively.

3.2 THEORETICAL ANALYSIS

3.2.1 Data Modulation Formats

In single mode optical fibers, information is carried in three physical attributes, namely, intensity, polarization and phase (including frequency). The different data modulation formats are distinguished on the basis of these attributes. To generate optical modulation format, NRZ-OOK is the simplest way in which the system only transmits when the user has data to send, otherwise not. Pulse carver can be used to generate RZ-OOK. But the intensity modulation formats becomes inefficient as the data rate is increased.

DPSK is a phase modulated format in which information is encoded in the change in binary phase between adjacent bits: 1-bit is represented by a π phase change and 0-bit is encoded by the absence of a phase change. One can either use PM or MZM to perform optical phase modulation. The bandwidth of PM and driver amplifier limits the speed of phase transitions, resulting in phase distortions. So mostly MZM is used as a phase modulator which gives exact phase transition, but at the cost of residual intensity dips at the position of phase transitions. For detecting information carried by the optical field's phase, converting elements from phase to intensity are required before the photodiode. The advantage of DPSK format is that it gives 3-dB receiver sensitivity improvement than OOK [22].

DQPSK is a multi-level modulation format which doubles the spectral efficiency by transmitting two bits at a time. The two incoming data streams are converted into a four phase optical data signal by using two nested MZMs which operate as phase modulators. A pre-coder is necessary to ensure that exactly the same data is received as has been transmitted. Hence, DQPSK has so far received an appreciable attention in optical fiber communications due to its capability to provide high spectral efficiency [58, 59].

3.3 SIMULATION DESCRIPTION

Figure 3.1 shows the simulation diagram in which the performance of four different optical modulation formats, namely, OOK, DPSK, NRZ-DQPSK and RZ-DQPSK is compared on the basis of BER vs. OSNR. To generate different values of OSNR, a white Gaussian noise source with noise power density of $0.8*10^{-15}$ is added, followed by an attenuator and optical band-pass filter with Gaussian transfer function of order 32. The NRZ-OOK transmitter consists of a continuous wave laser source at 193.1 THz and an information source of Pseudo Random Binary Sequence (PRBS) of order 7. The modulation is performed by MZ modulator and the modulated signal is passed through a noiseless amplifier which is finally received by OOK receiver which uses stochastic method to estimate BER. In case of DPSK, the modulation is performed by a dual drive phase modulator with extinction ratio = 35 dB in push-pull configuration which is driven by a NRZ data stream. This gives phase modulation with a near-perfect 180^0 phase shift. At the receiver side, a delay line interferometer is used to detect the optical signal and bit stream is extracted to calculate the BER of DPSK system to be compared.

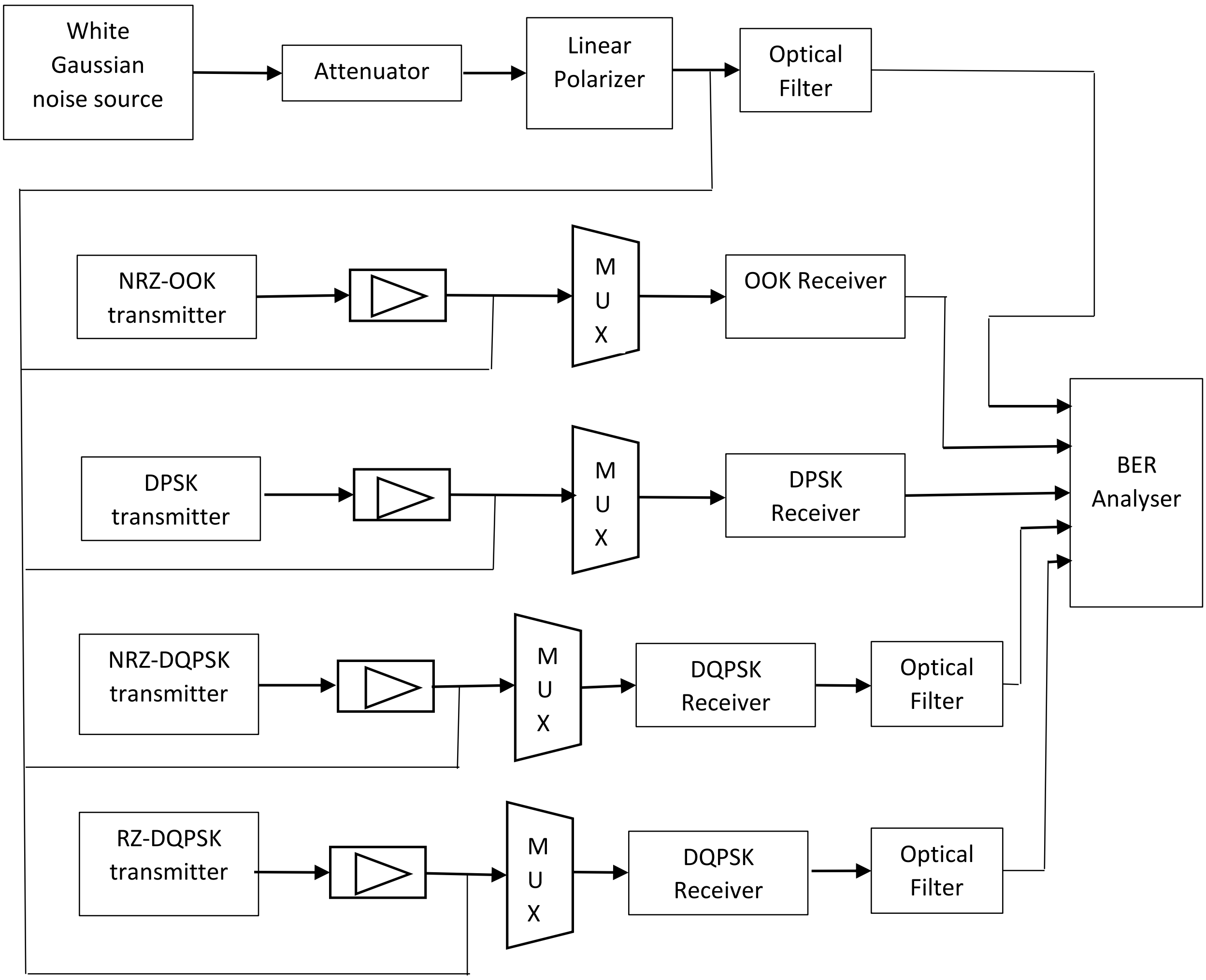


Figure 3.1 The simulation set-up for comparison of different modulation formats

The next modulation format that is being compared is the multi-level modulation format, DQPSK, in both NRZ and RZ format. In DQPSK transmitter, difference in optical phase $(0, \frac{\pi}{2}, \pi, \frac{3\pi}{2})$ between successive bits is used to encode information. So two bits of information is transmitted per symbol which gives symbol rate equal to half the total bit rate. It consists of digital precoder and an optical encoder, comprising of 3-dB optical power splitter, two parallel MZMs, an optical phase shift and an optical power combiner. After a relative optical phase shift of $\frac{\pi}{2}$, the in-phase (I) and quadrature (Q) signals are combined to give the modulated signal [60]. An optical band-pass filter is used at receiver side with Gaussian transfer function and the filtered signal is received by DQPSK receiver which consists of two DPSK receivers and hence, calculates BER. These formats are compared with the help of analyser.

3.4 RESULTS AND DISCUSSIONS

The values of BER for four different modulation formats are taken from the respective receivers and given to the analyser. A white Gaussian noise source is used to generate various values of OSNR. Figure 3.2 represents the plot for BER vs. OSNR for OOK, DPSK, NRZ-DQPSK and RZ-DQPSK at bit rate of 40 Gb/s. As the value of OSNR is increased, the BER is decreased linearly for all the modulation formats. For an OSNR requirement of 20 dB, the BER for OOK is 10^{-4} and for BER = 10^{-9}, the OSNR required for OOK is 23.6 dB, which is the maximum in all the four cases. When we move on to DPSK format, there is a large difference in the slopes of OOK and DPSK, which clearly defines drastic reduction of BER for DPSK. For BER = 10^{-9}, OSNR required for DPSK is 21.3 dB. So there is an improvement of 2.3 dB in OSNR requirement for DPSK than OOK for BER = 10^{-9}.

The plot for NRZ-DQPSK shows further reduction in BER for OSNR = 20 dB as it goes to BER = 10^{-8}. There is a small difference between the BER slopes of DPSK and NRZ-DQPSK. For BER = 10^{-9}, NRZ-DQPSK requires an OSNR of 20.6 dB. So almost 0.7 dB improvement over DPSK and 3 dB improvement over OOK. There is a very small difference in the BER slopes of NRZ-DQPSK and RZ-DQPSK. They exchange their slopes

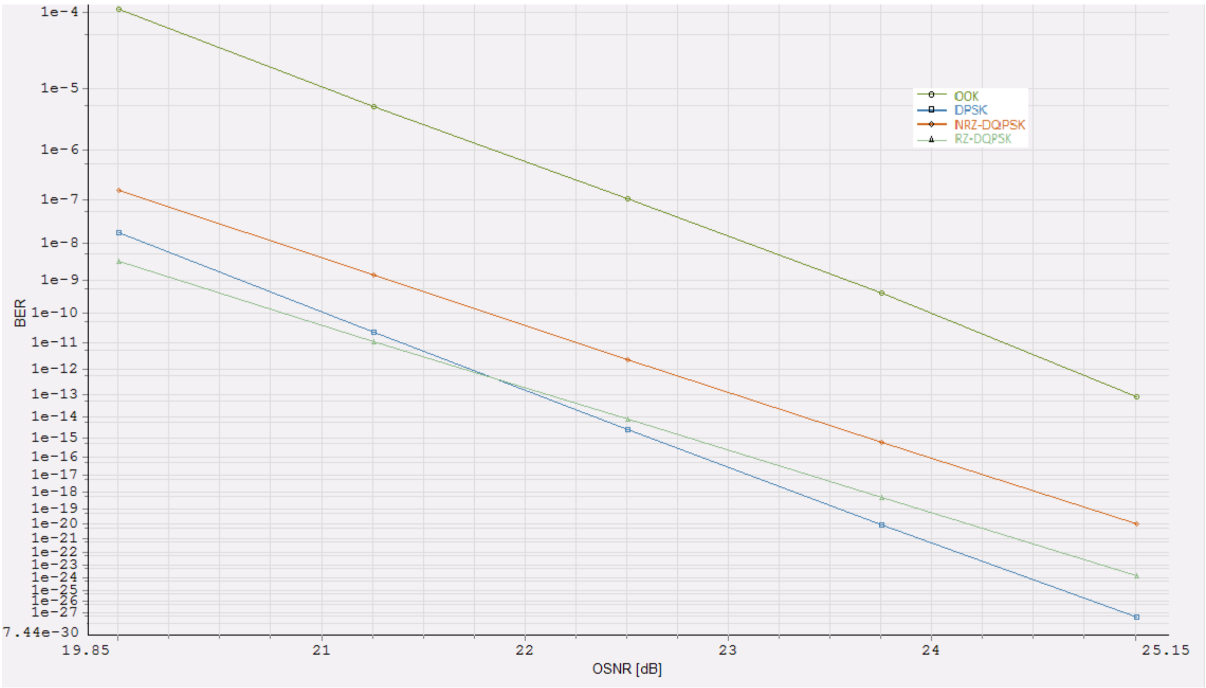
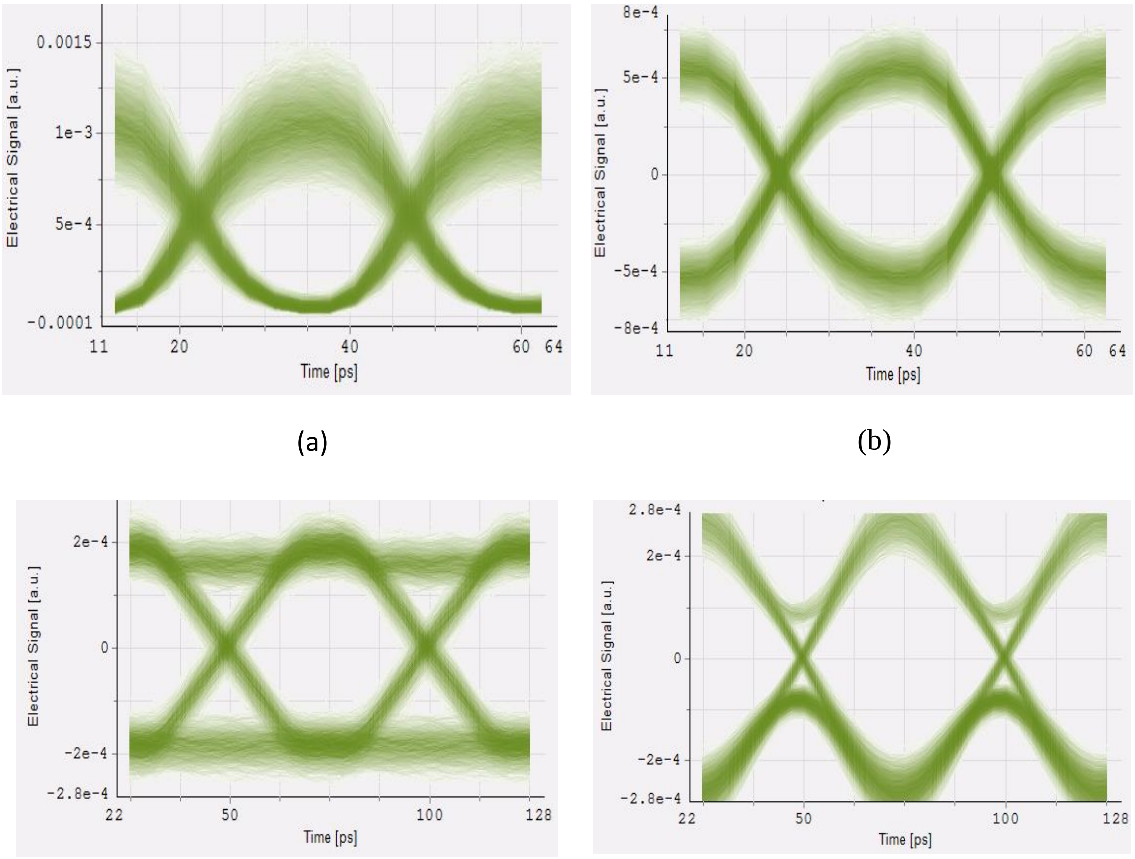


Figure 3.2 BER vs. OSNR for OOK, DPSK, NRZ-DQPSK and RZ-DQPSK formats at 40Gb/s.

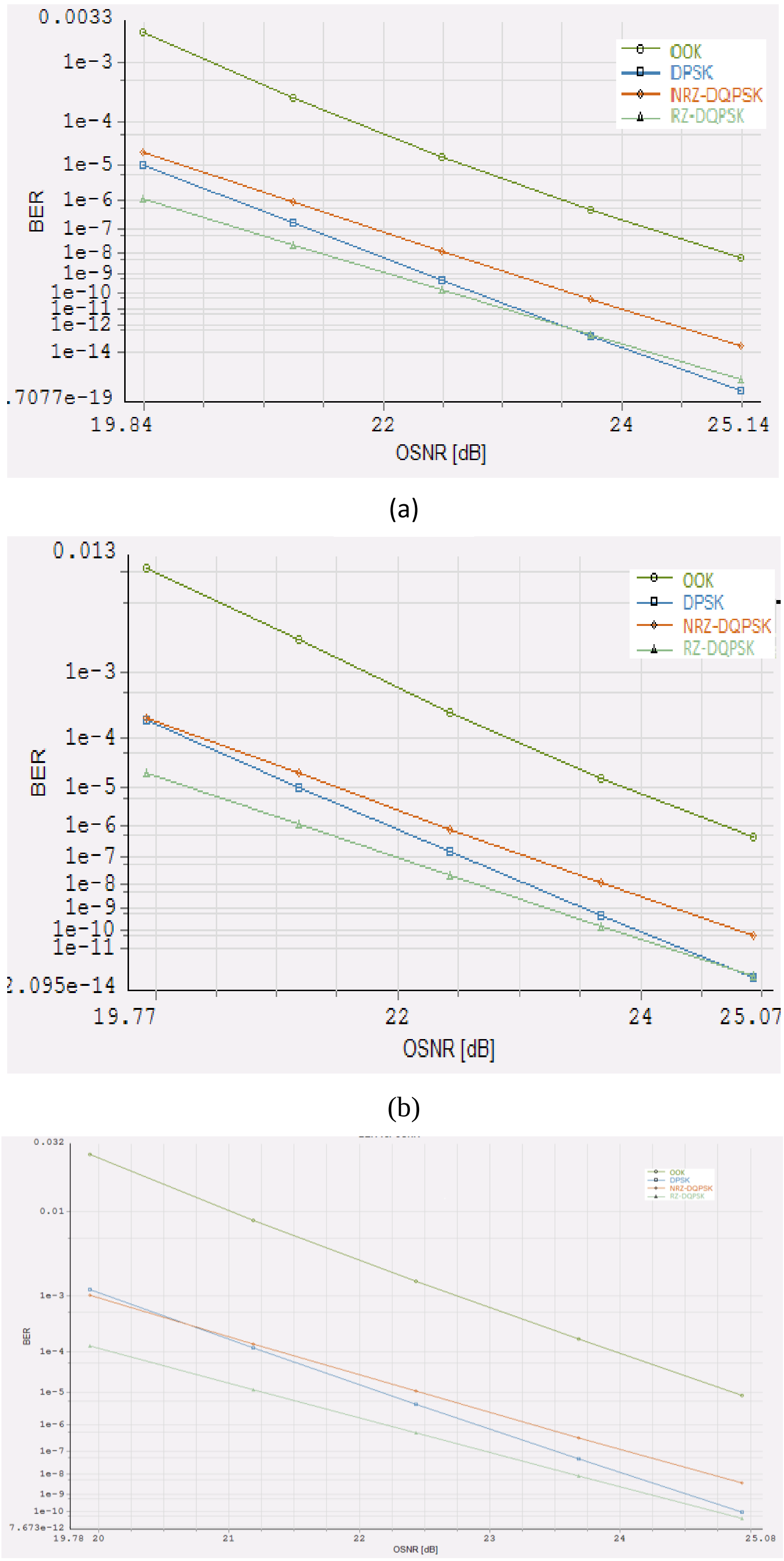
almost at 21.75 dB. So for OSNR = 20 dB, the minimum BER = 10^{-9} for RZ-DQPSK. For BER = 10^{-9}, OSNR required is also the minimum among all the four modulation formats, that is, 20.3 dB. So there is an improvement of 0.3 dB in OSNR requirement for BER = 10^{-9} in case of RZ-DQPSK system. Therefore, RZ-DQPSK gives the best BER results. Figure 3.3 depicts the eye diagrams of all the four formats at 40 Gb/s. Eye diagram shows the height and width of the eye opening. When the received signal is clear, then height and width of the eye opening is large. The noise margin is represented by the height of the eye opening whereas time interval over which distortion-less received signal can be sampled is represented by the width of the eye opening. It is very much clear from the eye diagrams that RZ-DQPSK gives the most distortion-less received signal among all the formats described.



(a) (b)

(c) (d)

Figure 3.3 Eye diagrams for (a) OOK, (b) DPSK, (c) NRZ-DQPSK and (d) RZ-DQPSK formats respectively at 40Gb/s.



(a)

(b)

(c)

Figure 3.4 BER vs. OSNR for OOK, DPSK, NRZ-DQPSK and RZ-DQPSK formats at (a) 60Gb/s (b) 80 Gb/s (c) 100 Gb/s.

Figure 3.4 depicts the values of BER against OSNR in dB for different values of bit rate of 60 Gb/s, 80 Gb/s and 100 Gb/s. When the data rate is increased from 40 Gb/s to 60 Gb/s, 80 Gb/s and 100 Gb/s, the BER slopes for all the modulation formats are almost similar to slopes at 40 Gb/s. But the BER for each modulation format is increased. At 60 Gb/s, for an OSNR of 20 dB, the minimum BER obtained is 10^{-6} for RZ-DQPSK whereas the maximum BER = 0.0030 for OOK. For BER = 10^{-9}, the minimum OSNR required by RZ-DQPSK is 22 dB. So there is a performance degradation by 1.7 dB for RZ-DQPSK. When the bit rate is further increased from 60 Gb/s to 80 Gb/s, the most poor performance is exhibited by OOK which gives a maximum BER = 0.013 at OSNR = 20 dB. For RZ-DQPSK, there is an increase of 0.1 in the BER at OSNR = 20 dB. At values of OSNR<20 dB, the BER performance of DPSK and NRZ-DQPSK is the same.

3.5 CONCLUSION

The evolution of data modulation formats from intensity modulated to multi-level modulated formats can provide high spectral efficient optical fiber communication systems at higher data rates. The transmission of different modulation formats, namely, OOK, DPSK, NRZ-DQPSK and RZ-DQPSK at various values of OSNR is discussed. The performance of these formats with respect to different bit rates have been compared by means of numerical simulations. When these formats are compared at 40 Gb/s and 100 Gb/s, then RZ-DQPSK format shows the minimum variations in its BER for a particular OSNR. So, the RZ-DQPSK format has the maximum resilience against increase in bit rate in comparison to other described formats. Thus, high data rates can be achieved successfully by using multi-level modulation formats in optical fiber communication systems.

CHAPTER 4

TRANSMISSION OF 112 Gb/s POLMUX DQPSK SYSTEM

The performance of the multilevel modulation format, POLMUX DQPSK has been investigated at 112 Gb/s in this chapter by means of numerical simulations. The performance of transmission of 112 Gb/s dual carrier POLMUX NRZ-DQPSK is compared with that of dual carrier POLMUX RZ-DQPSK systems over 20 km of standard single mode fiber with respect to changes in State of Polarization (SOP). It is observed that POLMUX RZ-DQPSK systems gives an improvement of 1.25 dB in OSNR for BER=10^{-3} than POLMUX NRZ-DQPSK system. But the optical spectrum of POLMUX NRZ-DQPSK signal is much narrower than POLMUX RZ-DQPSK signal at the receiver side.

4.1 INTRODUCTION

Nowadays, there is a need for more bandwidth efficient modulation formats to transmit high data rates in more densely spaced WDM systems. Up until a few years ago, optical communication systems primarily employed binary modulation formats for modulating the information on the optical carrier. But they cannot perform in 100G transmission systems due to limited opto-electronics bandwidth and OSNR. It restricted the theoretically achievable spectral efficiency to 1 b/s/Hz [61], assuming no overhead is required for FEC.

A further increase in spectral efficiency of WDM systems requires the use of multi-level modulation formats, using either modulation in the amplitude, phase or polarization domain. Among different possible approaches, Polarization multiplexing together with the DQPSK format is viewed as a promising modulation format for 100 Gb/s transmission links because of its narrow spectral width and robust tolerance to system impairments. Though polarization multiplexing may pose some problems with PMD, its PMD tolerance is much more than 100 Gb/s OOK signals [62].

Stefan Wabnitz [63] investigated the performance of 112 Gb/s transmission of both single channel and hybrid WDM POLMUX QPSK system with coherent receivers in the presence of fiber non-linearity and PMD, without in-line dispersion management. The distribution of errors and the associated outage probability is numerically estimated by the Importance Sampling technique, in the presence of fiber non-linearity and PMD.

Some researchers such as, Jinnan Zhang et al. [64] have considered POLMUX RZ-DQPSK as a good approach for implementation of signals at 100 Gb/s and above along with direct detection and automatic polarization tracking. They had exemplified this with the transmission of 112 Gb/s POLMUX RZ-DQPSK over 960 km. In this chapter, the transmission of dual carrier POLMUX DQPSK at 112 Gb/s is studied by means of numerical simulations. In particular, a comparison is made between POLMUX NRZ-DQPSK and POLMUX RZ-DQPSK systems in terms of tolerance to variations in degree of polarization which affect the BER of the system. In section 2, the multi-level modulation format POLMUX DQPSK has been described. Section 3 describes in detail the simulation set-up for the transmission of 112 Gb/s Dual carrier POLMUX DQPSK over 20 km of SSMF. Section 4 and section 5 contains the results and conclusion respectively.

4.2 THEORETICAL ANALYSIS

4.2.1 POLMUX DQPSK Modulation Format

A very narrow optical spectrum and long symbol period, compared to binary modulation formats, can be obtained by combining the two approaches towards multi-level modulation, that is, POLMUX and DQPSK, resulting in 4-bits/symbol modulation. In POLMUX, independent information in each of the two orthogonal polarizations is transmitted which doubles the spectral efficiency. But the main drawback of POLMUX is that it requires polarization sensitive detection due to random birefringence in optical fibers. However, the PMD tolerance of POLMUX signals is still more than that of binary modulation formats [65], [66]. So POLMUX when combined with DQPSK gives promising transmission results while maintaining sound filtering tolerances along with high robustness against chromatic dispersion and PMD with respect to binary modulation formats. In [67], the feasibility of transmission with a 2.5 b/s/Hz spectral efficiency using POLMUX-RZ-DQPSK is investigated.

4.2.2 Degree of Polarization (DOP)

Degree of Polarization (DOP) is one of the PMD monitoring technique, and it can be expressed as [68]

$$DOP = \frac{\left|\int_{-\infty}^{\infty} \mathrm{S}(\omega)\mathrm{S}_0(\omega)\mathrm{d}\omega\right|}{\int_{-\infty}^{\infty} \mathrm{S}_0(\omega)\mathrm{d}\omega} \tag{5}$$

where $S(\omega)$ is the Stokes vector and $S_0(\omega)$ is the optical power which is a measurement of the average SOP over the modulation bandwidth, weighted by the power spectrum. The above equation can be solved to express PMD-induced penalty as a function of DOP for the first-order PMD model

$$\varepsilon_{DB}(DOP) = \frac{A}{(\alpha T)^2}(1 - DOP^2) \tag{6}$$

where A is the system specific constant that depends on the transmitter and receiver characteristics.

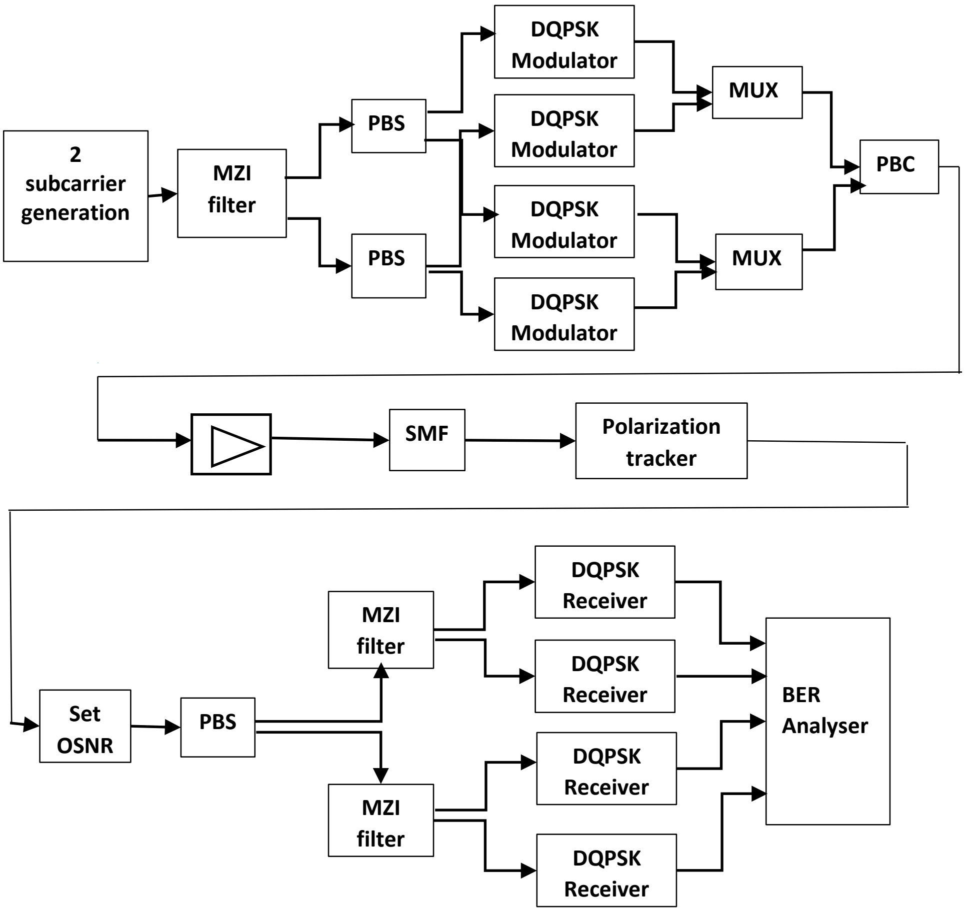


Figure 4.1 Simulation diagram of dual carrier POLMUX DQPSK system

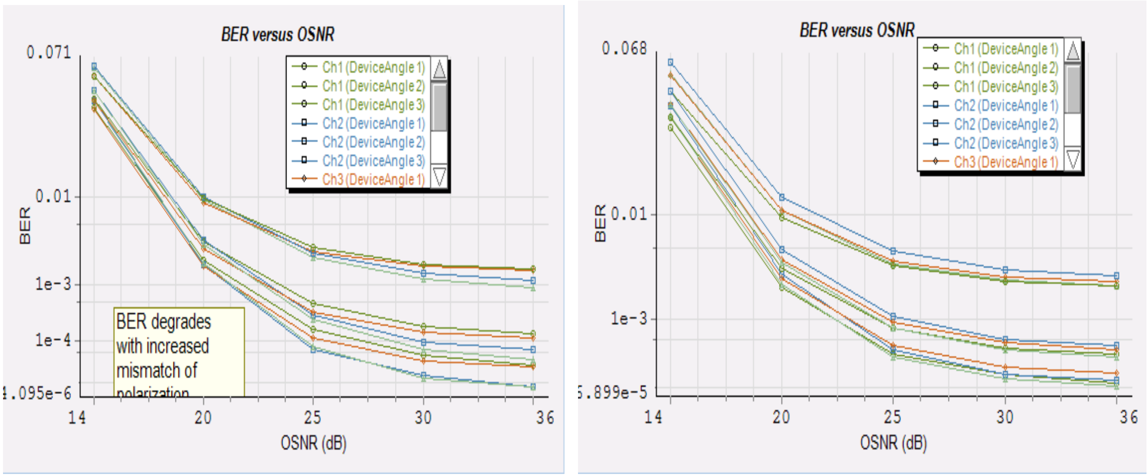
4.3 SIMULATION DESCRIPTION

The simulation set-up of 112 Gb/s dual carrier POLMUX NRZ-DQPSK system is shown in Figure 4.1. At the transmitter side, a Continuous Wave (CW) optical at 193.12 THz is fed to the MZM which converts the single carrier into two subcarrier signals with spacing of 28 GHz. It is followed by a delayed MZI with Free spectral range of 60 GHz to split the two carriers. Then these carriers are individually passed through Polarization Beam Splitters (PBS) to split them into orthogonal polarizations. These polarized beams are connected to four DQPSK modulators, followed by two Multiplexers (MUX) for x and y polarized beams respectively. They are combined by polarization beam combiner and sent through SSMF over 20 km after amplification.

After fiber transmission, the polarization tracker is used to adjust the SOP to separate the two polarization channel. At the receiver side, PBS is used to split the signal into both orthogonal polarizations again. We can analyse the performance of POLMUX NRZ-DQPSK and POLMUX RZ-DQPSK systems by creating mismatch in polarizations by changing the device angle of PBS. The polarized signals are passed to two MZI- based filters with 60 GHz FSR before DQPSK demodulation and then the detected signals are sent to the BER analyser.

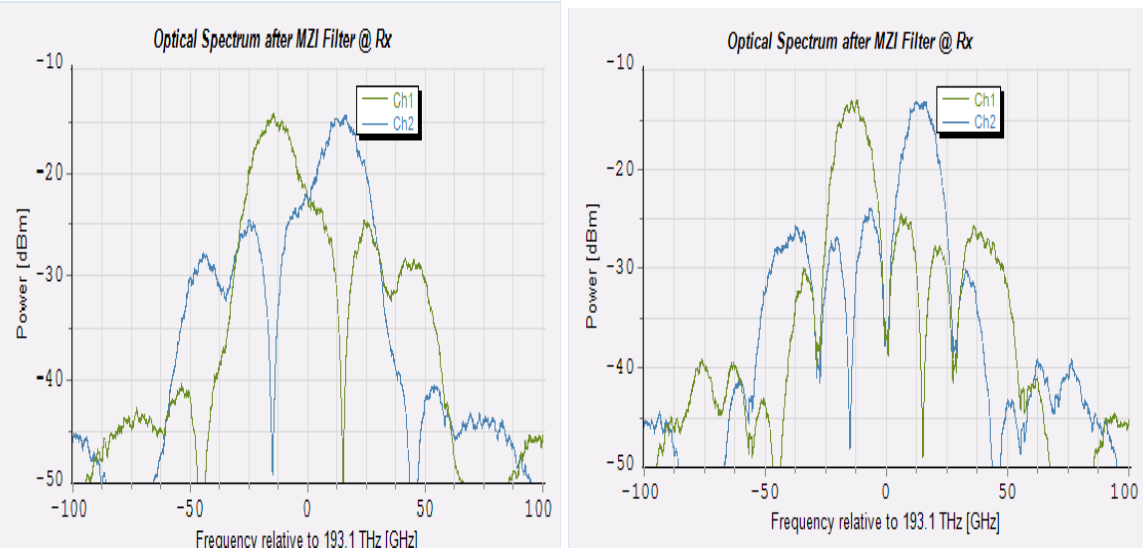
4.4 RESULTS AND DISCUSSION

The performance of transmission of 112 Gb/s dual carrier POLMUX RZ-DQPSK and dual carrier POLMUX NRZ-DQPSK systems has been analysed for SSMF over 20 km when the device angle of PBS is varied from 0^0 to 10^0 by means of numerical simulations. Figure 4.2 shows the plot of BER vs. OSNR of four channels at device angles of 0^0, 5^0, and 10^0respectively. Here it is seen that when the device angle is increased from 0^0 to 10^0, BER increases sharply from 0.05 to 0.071 in case of dual carrier POLMUX RZ-DQPSK and from 0.046 to 0.068. So when the polarization mismatch increases, the BER performance continues to degrade for both the systems. Figure 4.3 represents the optical spectrum of dual carrier POLMUX RZ-DQPSK and dual carrier POLMUX NRZ-DQPSK systems at the receiver side after MZI filter. The spectra of 28 Gbaud POLMUX NRZ-DQPSK and POLMUX RZ-DQPSK signals is compared and it is found that the main spectral and side lobes of POLMUX NRZ-DQPSK system are much narrower and more suppressed than POLMUX RZ-DQPSK as displayed in Figure 4.3.



(a) (b)

Figure 4.2 BER vs. OSNR for various device angles of (a) Dual carrier POLMUX RZ-DQPSK (b) Dual carrier POLMUX NRZ-DQPSK system.



(a) (b)

Figure 4.3 Optical spectrum of (a) Dual carrier POLMUX RZ-DQPSK (b) Dual carrier POLMUX NRZ-DQPSK system

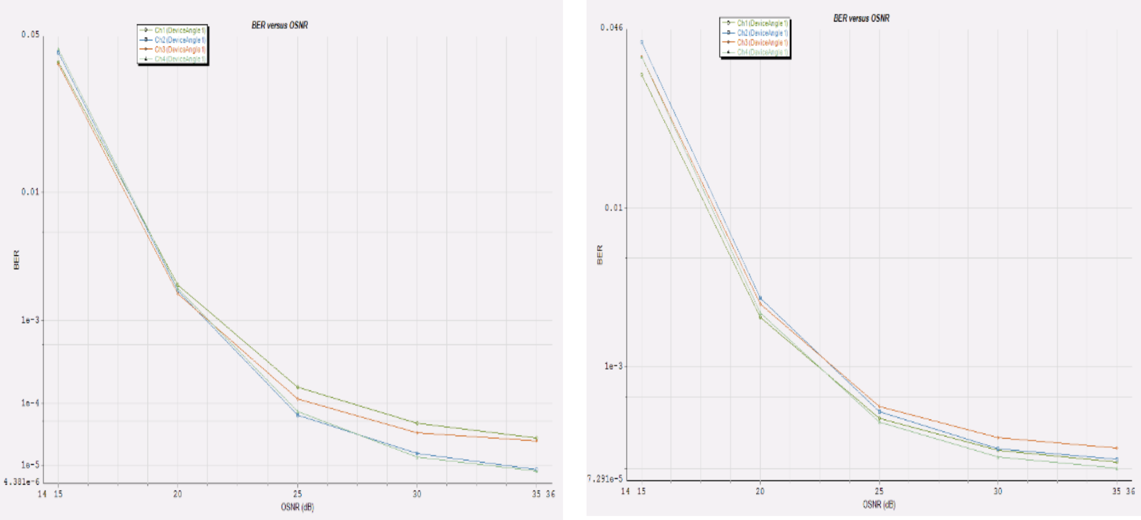


Figure 4.4 BER vs. OSNR for device angle 0^0 of (a) Dual carrier POLMUX RZ-DQPSK (b) Dual carrier POLMUX NRZ-DQPSK system

Figure 4.4 depicts the performance of dual carrier POLMUX RZ-DQPSK and dual carrier POLMUX NRZ-DQPSK systems at a device angle of 0^0. It is observed that the BER performance of POLMUX RZ-DQPSK system is better than that of POLMUX NRZ-DQPSK system as the curve for the former system is less sharp than the latter. For BER=10^{-3} at device angle of 0^0, OSNR required for POLMUX RZ-DQPSK system is 21.25 dB whereas for POLMUX NRZ-DQPSK system, it is 22.5 dB. Therefore, POLMUX RZ-DQPSK systems gives an improvement of 1.25 dB in OSNR for BER=10^{-3} than POLMUX NRZ-DQPSK system.

4.5 CONCLUSION

Multi- modulation formats can help to increase the robustness of optical transmission due to high data rate with respect to the symbol rate. DQPSK modulation when combined with POLMUX enables transmission with high spectral efficiency. Dual carrier POLMUX RZ-DQPSK gives better BER performance than dual carrier POLMUX NRZ-DQPSK system at transmission of 112 Gb/s but the system performance degrades when there is increase in polarization mismatch. Therefore, due to influence of PMD-related impairments, improvements in transmission tolerances are required, which pose a great challenge for their long haul transmission.

CHAPTER 5

TRANSMISSION OF 112 Gb/s POLMUX QPSK SIGNAL

In this chapter, the impact of XPM and XpolM on transmission of 112 Gb/s POLMUX QPSK signal in a WDM system comprising of OOK or DPSK channels has been investigated. It is observed that for a hybrid system of co-propagating OOK and DPSK channels, the effects of XPM and XpolM are greatly reduced due to the dominance of phase modulation of DPSK signals rather than the intensity modulated OOK signals. The EVM of the received optical signal is evaluated for the increase in number of neighbouring OOK and DPSK channels respectively within a bandwidth of 350 GHz. Also, the effect of increase in bit rate for two neighbouring OOK and DPSK channels has been observed individually on the 112 Gb/s POLMUX QPSK signal. It is concluded that DPSK signals displays an improvement of -9.44dB in EVM over OOK signals when there are eight neighbouring channels in the transmission system.

5.1 INTRODUCTION

The information society of today relies on broadband communication solutions to an unprecedented extent, with applications such as mobile voice and data services, high-speed internet access, multimedia broadcast systems and high-capacity networking of data. With the increasing popularity of high-bandwidth applications and occupancy of the available transmission window of Single Mode Fiber (SMF), the high-capacity transmission and new detection technology have become extremely important. This is because of their potential to decrease the cost per transmitted bit by sharing of the fiber and optical components over more capacity. The technologies employing DWDM and EDFA have been proposed since 1990’s, to enhance the capacity by using OOK, modulation format with direct detection up to 10 Gb/s per channel. To optimize the performance of already deployed light-wave systems, both service providers and researches have concentrated their efforts to use different techniques to compensate for dispersion [69, 70] and other non-linear effects. Thus, the increasing growth in network calls for the need to transport 100 Gb/s signals over existing optical fiber communication network. Hence, the use of spectrally efficient modulation formats becomes of utmost significance.

The modulation formats using POLMUX signals appears to be strong candidate for spectrally efficient DWDM transmission systems with high bit rates of 40 Gb/s and 100 Gb/s [71, 72]. In comparison to conventional non-POLMUX formats, POLMUX signals enables large tolerances to PMD and CD as well as doubled spectral efficiency due to their additional degree of freedom in polarization domain. In particular, POLMUX with coherent transmission of QPSK signals have been the subject of high interest for many researchers. The potential of such systems for several long-haul experiments [73] has proven to be remarkable. As a result, POLMUX QPSK is becoming one of the most promising technology for next generation of high-capacity and long-haul optical transmission systems.

Besides the inherent advantages of the QPSK modulation format, the main degrading factor, when mixed with different modulation formats on the WDM systems, is its limited tolerance to XPM that is caused by the neighbouring intensity modulated or the phase modulated channels. Many studies [74, 75] have already established this fact that XPM is the main impairment on QPSK channels in hybrid systems.

In 2009, Alberto Bononi et al. [76] presented a theoretical framework which modelled the channel interactions among QPSK and OOK systems in hybrid WDM systems. The estimation of channel impairments induced by XPM of lower rate OOK channels on higher rate coherent QPSK and incoherent DQPSK systems has been provided by a well-known linear model along with sensitivity penalty analytical expressions. They proved that QPSK penalty due to XPM is decreased with the increase in baud rate of QPSK by the phase estimation process. It has been concluded that at the same baud rate, incoherent DQPSK is less impaired by XPM than coherent QPSK when feed forward estimation is performed.

Earlier, the research has been done to study the impact of cross-polarization modulation (XpolM) effect so that differences between XPM and XpolM effects can be analysed in a 112 Gb/s POLMUX QPSK channel over 10 Gb/s legacy system [77]. The impact of XpolM has been found out to be smaller than that of intra-channel nonlinearities and the impact of XPM.

This research work examines the impact of XPM and XpolM on 112 Gb/s POLMUX QPSK signal in a WDM system with different number of OOK or DPSK channels. Also, their impact with changes in bit rate have been studied. This chapter is organised as follows: Section 2 gives an overview of the effects of the XPM and XpolM. Section 3 describes the simulation set-up for the transmission of 112 Gb/s POLMUX QPSK signal in a WDM system of OOK/DPSK channels. Section 4 and 5 contains the results and conclusions respectively.

5.2 XPM and XpolM

XPM is one of the most important nonlinear phenomenon which arise due to intensity dependence of the refractive index. It occurs due to simultaneous transmission of two or more optical fields in an optical fiber. There is inter-channel crosstalk produced due to GVD caused by intensity fluctuations in the neighbouring channels which are induced due to the nonlinear phase modulation through XPM. In WDM systems, the phase-modulation efficiency of XPM is affected due to random SOP of all the WDM channels because of residual birefringence fluctuations that occur in any optical fiber. For POLMUX QPSK signals, there is fading and channel cross-talk due to depolarization of the transmitted signal caused by fast polarization-modulation of signals, thus resulting in XpolM. XpolM-induced depolarization, when looked at a particular channel (probe), depends on the variance of Stokes vector of all the co-propagating channels (pump). The variation of SOP of the probe signal, as expressed in Stokes space, is described by its Stokes vector, $\vec{s}$ which is given by [78, 79]:

$$\frac{\partial \vec{s}}{\partial z} = \frac{8}{9}\,\gamma \overrightarrow{s_T} \times \vec{s} \tag{7}$$

where $\overrightarrow{s_T}$ is the Stokes vector of all the pump and probe signals. It is to be noted that the equation (7) can also be written as:

$$\frac{\vec{s}}{\partial z} = \frac{8}{9}\,\gamma \vec{p} \times \vec{s} \tag{8}$$

when the pump signal’s power is much greater than that of the probes signal, which means there is rotation of the probe channel due to XpolM. Also, there is no polarization modulation when the SOPs of the pump and probe signals are identical or orthogonal.

5.3 SIMULATION DESCRIPTION

The simulation set-up consists of a CW laser source with average power of 10^{-4}, operating at a frequency of 193.1 THz to produce a CW optical signal. This is given to the POLMUX QPSK transmitter, as shown in Figure 5.1. It comprises of a PBS which splits the incoming

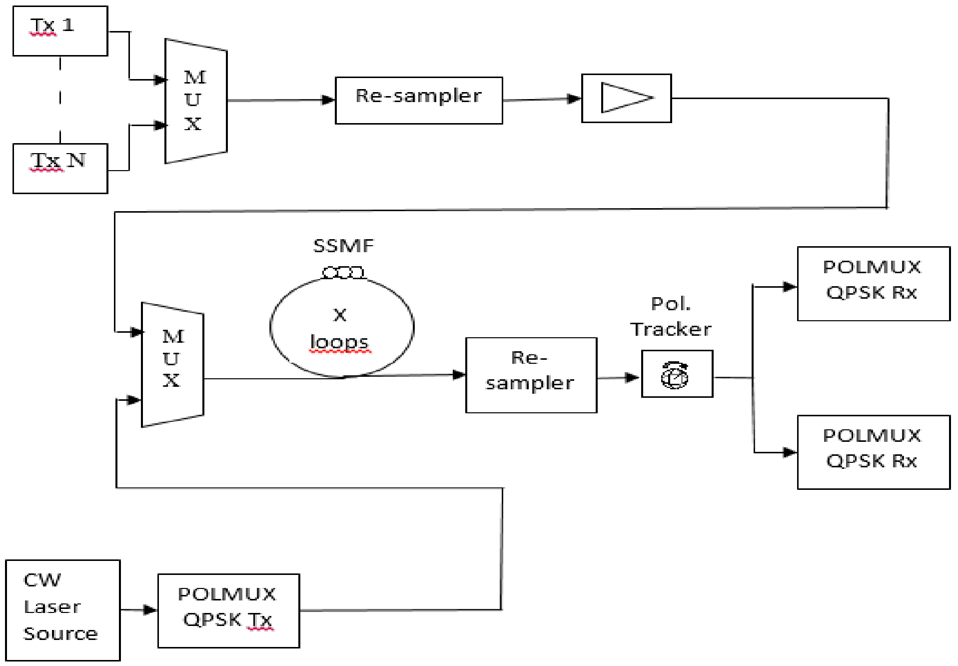


Figure 5.1 Simulation diagram of the 112 Gb/s POLMUX QPSK signal with co-propagating channels

optical signal into two polarization components, that is, X- component and Y-component. Both of these components are modulated individually by a QPSK transmitter, consisting of a single drive MZM at an extinction ratio of 35 dB and Low Pass Filter (LPF) of order 4. An electrical I-Q coder-driver is used to generate the driving signals, which consists of I-Q encoder along with the pulse-shaping filters to allow pre-distortion for the driving signal to compensate for MZM non-linearity. These modulated components are multiplexed by a WDM multiplexer to produce the POLMUX optical signal.

To analyse the impact of neighbouring channels on a 112 Gb/s POLMUX QPSK signal, different number of NRZ-OOK and DPSK transmitters are used at different bit rates. The NRZ-OOK transmitter consists of a CW laser source and PRBS generator of order 7, that are modulated by differential MZM. Whereas the DPSK transmitter comprises of a CW laser at a frequency of 193.1 THz and PRBS of alternate type followed by a dual-drive PM in push-pull configuration at an extinction ratio of 35 dB which performs phase modulation with a near-perfect 180^0 phase shift. The different number of NRZ-OOK or DPSK signals are individually multiplexed by the Nx1 multiplexer with an insertion loss of 0 dB and then resampled to modify the centre frequency and sample rate which is equal to the spectral width of an optical band. This is followed by an EDFA of output power equal to 4 mW and gain of 100 dB. The resulting signal is then multiplexed with the POLMUX optical signal and given to the spectrum analyser. Also, the combined WDM signal travels through 10 loops of SSMF of length 5 km at zero dispersion but taking into account the electronic contribution of XPM. This signal is then resampled at centre frequency of 193.1 THz, followed by the polarization tracker to restore the SOP of the signal that is affected by PMD and other distortions. It is then finally received by the POLMUX QPSK receiver.

The power penalty associated with this multi-level signal is mitigated by the coherent detection, which consists of mixing the received optical signal with a local light source at a frequency of 193.1 THz and average power of 10 mw. The local oscillator is followed by a PBS which splits the light into X- polarized and Y-polarized components respectively by the 90^0 hybrid, followed by a photodiode in the presence of shot noise and thermal noise. The signal is then filtered by the LPF with Bessel transfer function of order 4 and bandwidth of 42 GHz. These filtered components are then combined to produce the received signal through which error EVM is estimated along with the constellation diagrams. The I-Q components of the Y-polarized signal are ignored at the receiver side in this analysis.

5.4 RESULTS AND DISCUSSIONS

The transmission of 112 Gb/s POLMUX QPSK at 1550 nm together with different number of neighbouring channels at different bit rates has been carried out by means of simulations in VPI. Figure 5.2 shows the individual optical spectrums of 112 Gb/s POLMUX QPSK signal along with the two co-propagating OOK channels at 10 Gb/s with channel spacing of 50 GHz between OOK channels. This is observed after the multiplexing of the signals at the transmitter side. It gives measurement of optical power as a function of frequency relative to 193.325 THz. For POLMUX QPSK signal, the main lobe is broader and the side lobes are distinctly visible even at such a high bit rate of 112 Gb/s whereas in the optical spectrum of OOK signals, the main lobe is much narrower and the side lobes are not clearly defined at a bit rate of 10 Gb/s. Also, there is slight overlapping of the side lobes in OOK due to less channel spacing between them.

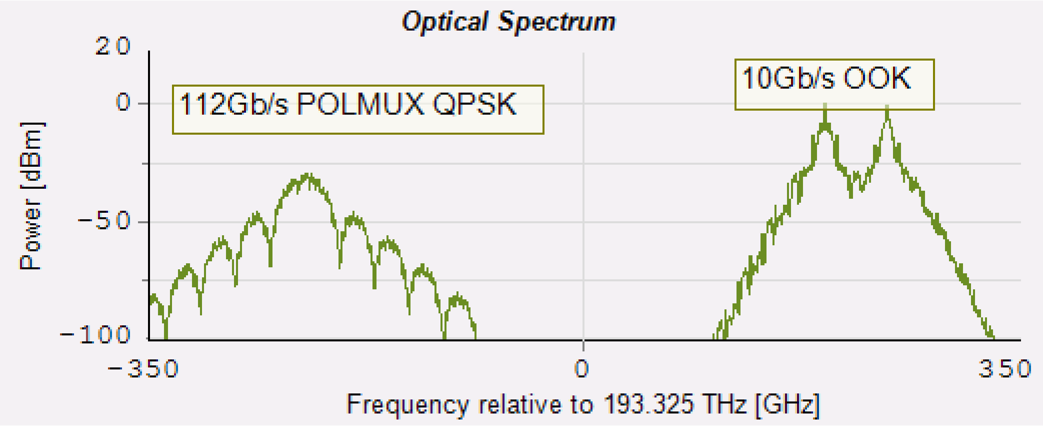
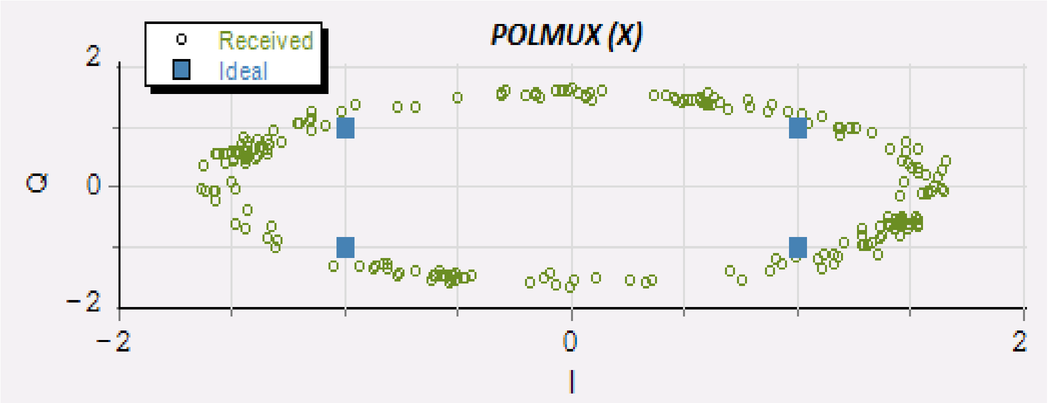


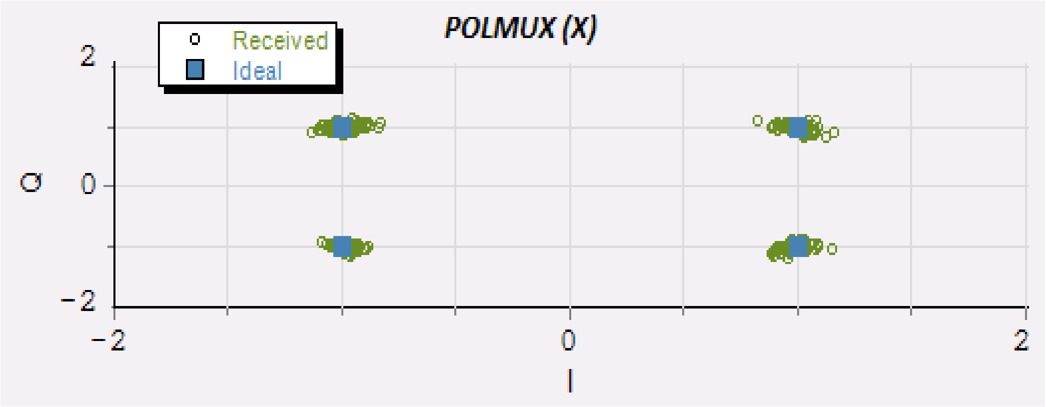
Figure 5.2 Optical spectrum of 112 Gb/s POLMUX QPSK and two co-propagating OOK channels after multiplexing.

Figure 5.3(a) and 5.3(b) depicts the constellation diagrams of the X-polarized component at the receiver side for four co-propagating OOK and DPSK channels at 10 Gb/s respectively. It is obtained when both the I and Q channels are sampled at the same instant and then plotted against each other. The blue square points represents the ideal constellation points for the 112 Gb/s POLMUX QPSK whereas the green circular points shows the received constellation points after getting received by the POLMUX QPSK receiver. The scattering of received constellation points for the case of OOK neighbouring channels is more in comparison to that of DPSK channels which accounts for the more pronounced effects of XPM and XpolM imposed by the co-propagating OOK channels than neighbouring DPSK channels in POLMUX QPSK signal. So when a hybrid system of two OOK and two DPSK channels (OOK, DPSK, OOK, DPSK) with a channel spacing of 50 GHz is taken into consideration, then the effect of XPM and XpolM on the transmission system is diminished as can been in the constellation diagram shown in Figure 5.3(c). The EVM of the received optical signal in this case is -12.83 dB.

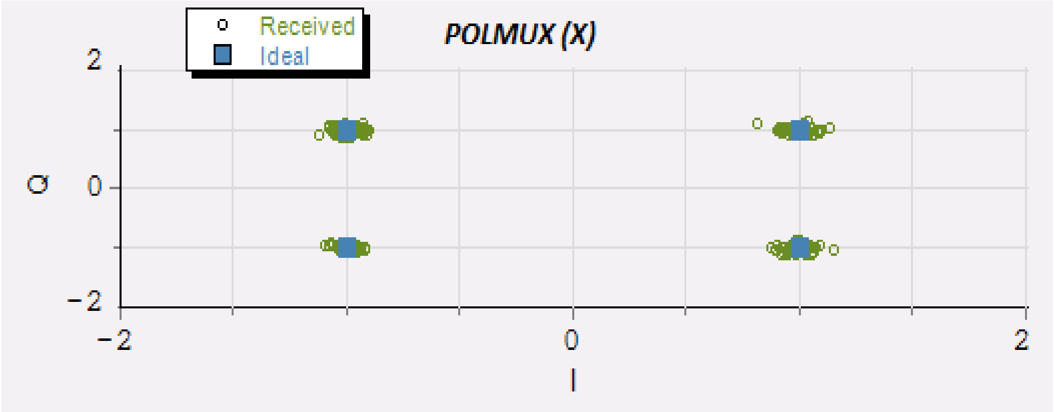
One of the methods to describe the polarization states of an optical signal is Stokes vector which can be represented by a Poincare sphere as shown in Figure 5.4(a). It shows the initial POLMUX QPSK signal after transmission along with the received optical signal (with four OOK channels at 10 Gb/s) after ideal polarization tracking.



(a)



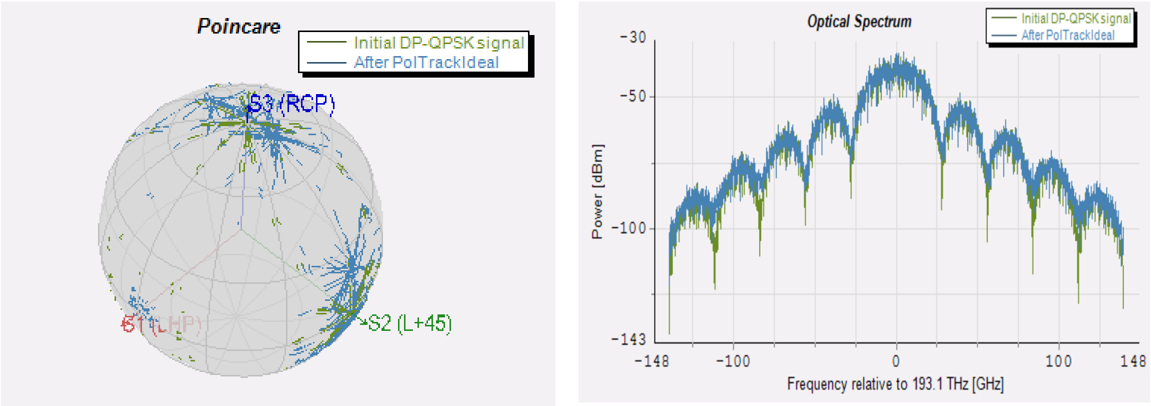
(b)



(c)

Figure 5.3 Constellation diagram of ideal and received optical signal for four neighbouring (a) OOK channels, (b) DPSK channels and (c) hybrid WDM system OOK and DPSK channels at 10 Gb/s.

In Stokes vector, S_0 is typically normalized to be 1 as the polarization state is not affected by the total intensity. S_1 gives the amount of energy in x or y direction, S_2 represents the amount of energy in the direction which is $\pm 45^0$ to the horizontal direction and S_3 gives the amount of energy that is Left-handed Circularly (LHC) polarized or Right-handed Circularly (RHC). A dispersion-less and lossless fiber with constant birefringence has been considered, for the sake of simplicity in this case in order to maintain constant SOPs of the pump and probe signals over the transmission system. Also, the corresponding optical spectrum for the received signal after ideal polarization tracking is shown in Figure 5.4(b) which depicts the role of adjusting the SOP of the received optical signal to obtain a clear and distinct view of major lobes and side lobes.

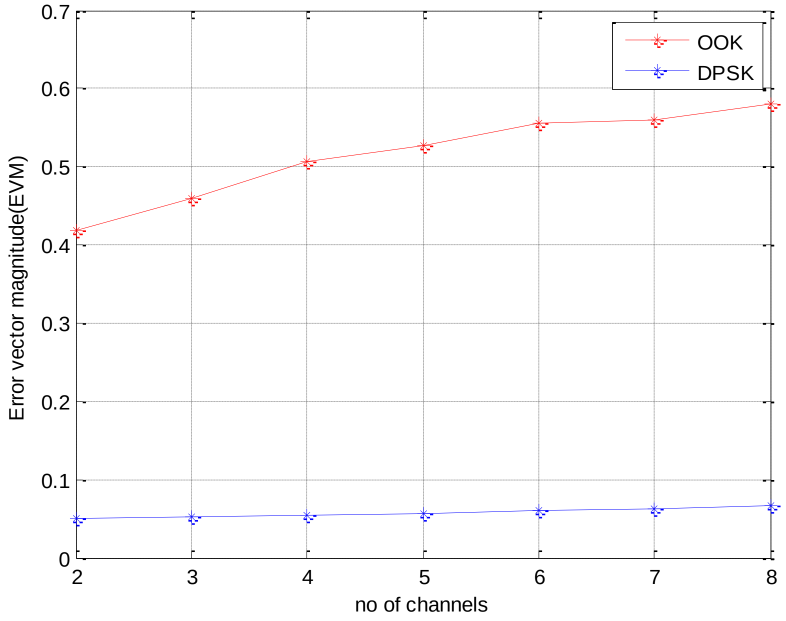


(a) (b)

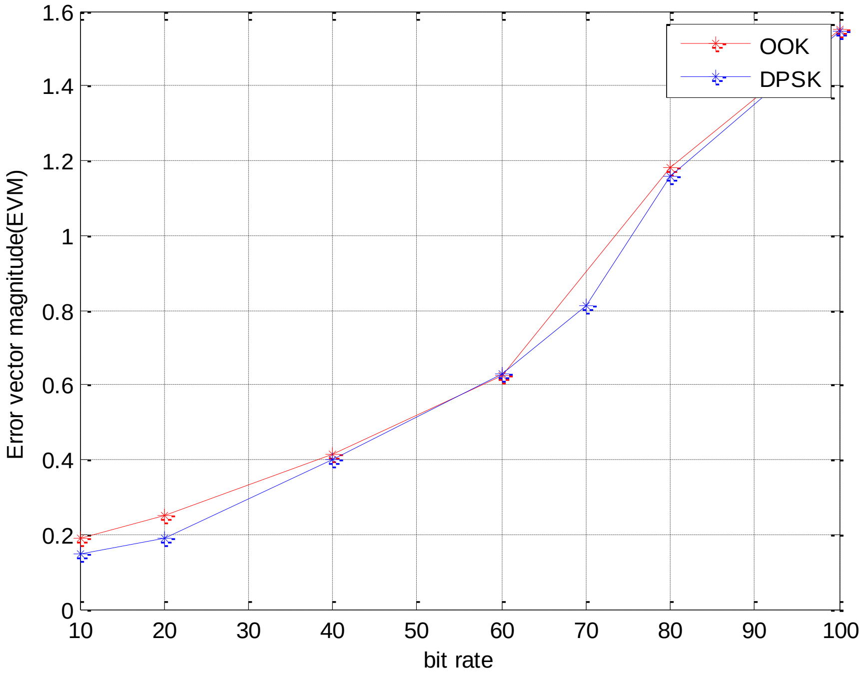
Figure 5.4 (a) Poincare of the received signal showing polarization tracking and (b) its corresponding optical spectrum.

Figure 5.5(a) depicts the plot of EVM of 112 Gb/s POLMUX QPSK received signal with different number of neighbouring OOK and DPSK channels at 10 Gb/s. The number of co-propagating channels are varied from two to eight, keeping a constant bandwidth of 350 GHz among the channels. EVM is one of the primary specification that can be used to determine the performance of the system in terms of transmitted and received symbols which correspond to a digital modulation scheme. It is observed that as the number of channels are increased, the EVM of the received signal is increased much more when there are OOK channels in the neighbourhood rather than DPSK channels. In case of OOK, the received POLMUX QPSK signal has EVM of -3.78 dB when the neighbouring channels are two which increases sharply to -2.36 dB when the number of OOK channels are eight.

Whereas the impact of neighbouring DPSK channels on the EVM of received POLMUX QPSK signal is much less when the number of channels are increased.



(a)



(b)

Figure 5.5 Plots showing (a) EVM of 112 Gb/s POLMUX QPSK received signal vs. number of channels and (b) EVM of 112 Gb/s POLMUX QPSK

It has a value of -11.80 dB when the channel count is eight. Also, the plot for EVM of 112 Gb/s POLMUX QPSK received signal against increase in bit rate for two co-propagating OOK and DPSK channels is shown in Figure 5(b). It shows an increasing trend for both the OOK and DPSK channels when the bit rate is enhanced from 10 Gb/s to 100 Gb/s but the EVM for OOK is found to be greater than DPSK channels.

5.5 CONCLUSION

The multiplexing of signals in the polarization domain is considered to be one of the methods to meet the ever-increasing demand of capacity in the optical fiber communication systems which offers a way to increase the spectral efficiency. But when these POLMUX signals are transmitted along with already laid network of OOK/DPSK channels, they suffer from the effects of XPM and XpolM. The performance of the transmission of 112 Gb/s POLMUX QPSK signals has been analysed when this signal propagates along with the neighbouring OOK/DPSK channels at a bit rate of 10 Gb/s. In a hybrid WDM system of alternate OOK and DPSK neighbouring channels, the effects of XPM and XpolM are greatly reduced. EVM is used as an evaluation parameter in order to compare the effect of increase in number of neighbouring OOK/DPSK channels. For eight number of co-propagating channels, DPSK signals shows an improvement of -9.44dB in EVM over the OOK signals. The impact of increase in bit rate for two neighbouring OOK and DPSK channels on 112 Gb/s POLMUX QPSK signals has been studied which shows that there is an improvement of -26.9dB in EVM for DPSK channels over OOK channels at 100 Gb/s. Therefore, due to XPM and XpolM effects, improvements in transmission tolerances of the POLMUX signals are required which pose a great challenge.

CHAPTER 6

CONCLUSION, RECOMMENDATIONS AND FUTURE SCOPE

6.1 CONCLUSION

The summary of the findings of the work done in the dissertation is provided in this chapter. Firstly, the conclusions drawn out of this study are discussed, followed by some suggestions regarding the future scope of this research work. The main results of this dissertation can be listed as follows:

1. The transmission performance of different optical data modulation formats, namely, OOK, DPSK, NRZ-DQPSK and RZ-DQPSK, has been discussed. These schemes were compared with each other at different values of data rate and the simulation results were evaluated in terms of BER and eye diagrams. At 40 Gb/s, there was a small difference between the BER slopes of DPSK and NRZ-DQPSK for an OSNR of 20 dB. When the OSNR was increased, all the optical modulation formats showed an increase in the values of BER but the maximum rise in BER was shown for OOK signal. When the bit rate was increased to 100 Gb/s, the BER is decreased by 0.01 for RZ-DQPSK format while it is decreased by 0.1 for OOK format, for 1 dB OSNR improvement. Also, at an acceptable BER of 10^{-9}, there is only an improvement of 0.25 dB in OSNR requirement for RZ-DQPSK than NRZ-DQPSK format at 100 Gb/s. The observed eye diagrams showed that the most distortion-less received signal among all the formats described in this chapter was obtained from RZ-DQPSK. Thus, it can be concluded that the RZ-DQPSK showed an appreciable performance at high bit rates.
2. The performance of the multilevel modulation format, POLMUX DQPSK for two carriers at the same wavelength has been investigated for various changes in SOP at 112 Gb/s, by means of numerical simulations. It was observed that when the device of PBS was varied from 0^0 to 10^0 in order to change the SOP, then there was a fall in the slope of BER plot. This was because of the polarization mismatch of the signals. Also, the performance of two formats: RZ and NRZ format of dual carrier POLMUX DQPSK transmission system at 112 Gb/s over 20 km of SSMF at a device angle of 0^0 were compared with each other. It was found that at

BER=10^{-3}, POLMUX RZ-DQPSK signals gives an improvement of 1.25 dB in OSNR over POLMUX NRZ-DQPSK signals. When their optical spectrums were compared, it was noticeable that the POLMUX NRZ-DQPSK signal had much narrower spectrum than POLMUX RZ-DQPSK signal at the receiver side. So the use of polarization multiplexing with DQPSK format can be a strong candidate for higher bit rates than 100 Gb/s that does not require DSP but with proper polarization control of the signals.

3. The impact of XPM and XpolM on transmission of 112 Gb/s POLMUX QPSK signal in a WDM system that comprised of OOK or DPSK channels has been studied and the results have been simulated in VPI Transmission Maker. EVM was taken as the evaluating parameter to plot against increase in the number of co-propagating channels within a bandwidth of 350 GHz at 10 Gb/s as well as against an increase in data rate. It was observed that when the number of neighbouring channels are increased to eight, the EVM was found out be -2.36 dB in case of OOK signals whereas its value was -11.80 dB for DPSK channels. When EVM was plotted against bit rate for two neighbouring OOK or DPSK channels, the EVM was found to be greater for OOK channels than DPSK channels for a rise in data rate from 10 Gb/s to 100 Gb/s. In addition, a hybrid WDM system comprising of total four alternating channels of OOK and DPSK signals at 10 Gb/s have been proposed which decreases the impact of XPM imposed by OOK channels on 112 Gb/s POLMUX QPSK signal.

6.2 RECOMMENDATIONS

The use of multi-level modulation format such as DQPSK is recommended for applications at higher bit rates as it gives less BER than the other optical modulation schemes compared in this dissertation.

The polarization multiplexed signals when combined with the other optical modulation schemes such as QPSK and DQPSK are believed to achieve even higher data rates, above 100 Gb/s. So in order to attain greater capacity for fiber optical communication system, these formats are recommended for achieving higher spectral efficiency.

A hybrid WDM system comprising of alternate OOK and DPSK channels at 10 Gb/s is suggested in this dissertation to minimise the effects of XPM and XpolM imposed by co-propagating OOK channels on transmission of 112 Gb/s POLMUX QPSK signals.

6.3 FUTURE SCOPE OF WORK

During the course time of this dissertation, several areas of interest come into picture for its continuation. The topics which are worthy to point out are summarized below:

In this dissertation, the fiber non-linearities, such as FWM, XPM, Stimulated Raman Scattering and Stimulated Brillouin Scattering have not been included while comparing different optical modulation schemes and while analysing the performance of POLMUX DQPSK signal. These effects are bound to degrade the performance of the optical communication system. So they can be further included in the fiber structure to investigate the overall performance of the system. Moreover, a way to electronically compensate for the degrading effects of the fiber linearities and non-linearities can be found out so that the system design could be more flexible.

During the investigation of performance of 112 Gb/s POLMUX QPSK signal in a WDM system, we have assumed a dispersion-less fiber and the effect of SPM has been neglected. Thus, dispersion can be considered in the fiber along with SPM effects for future research. In addition, the number of channels as well as the channel spacing in the co-propagating channels can be varied to observe their impact on the transmission system.

Further, the real world implementation of these POLMUX signals employing different optical modulation formats combined with the existing optical networks can be of great interest as they tend to increase the capacity of the transmission system. But their long-haul transmission can be a very challenging issue.

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List of Publications

[1] Harmanpreet Kaur Sandhu, and R. S. Kaler, “Transmission of 112 Gb/s Dual carrier POLMUX DQPSK system,” communicated to Optik.

[2] Harmanpreet Kaur Sandhu, and R. S. Kaler, “Comparison of Optical Modulation Formats at different Data Rates,” communicated to Optik.

[3] Harmanpreet Kaur Sandhu, and R. S. Kaler, “Transmission Performance of 112 Gb/s POLMUX QPSK Signal in OOK/DPSK WDM System,” communicated to Optik.