# Higher Order Modulation Formats for High Speed Optical Communication Systems with Digital Signal Processing Aided Receiver

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## Dedication

This thesis is dedicated to my family

**Declaration**

I, **Chabata Tichakunda Valentine**, **212410180**, hereby declare that this thesis for Ph.D award is my own work and that it has not previously been submitted for assessment in any University for any award.

**……………………………………**
Chabata Tichakunda Valentine

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## Abstract

The drastic increase in the number of internet users and the general convergence of all other communication systems into an optical system have brought a sharp rise in demand for bandwidth and calls for high capacity transmission networks. Large unamplified transmission reach is another contributor in reducing deployment costs of an optical communication system. Spectrally efficient modulation formats are suggested as a solution to overcome the problems associated with limited channels and bandwidth of dense wavelength division multiplexing (DWDM) optical communication systems. Higher order modulation formats which are considered to be spectrally efficient and can increase the transmission capacity by transmitting more information in the amplitude, phase, polarization or a combination of all was studied. Different detection technologies are to be implemented to suit a particular higher order modulation format. In this research multilevel modulation formats, different detection technologies and a digital signal processing aided receiver were studied in a practical optical transmission system.

The work in this thesis started with the implementation of the traditional amplitude shift keying (ASK) modulation and a differential phase shift keying (DPSK) modulation systems as they form the basic building block in the design of higher order modulation formats. Results obtained from using virtual photonics instruments (VPI)simulation software, receiver sensitivity for 10Gbpsnon-return-to-zero (NRZ), amplitude phase shift keying (ASK) and DPSK signals were measured to be -22.7 dBm and -22.0 dBm respectively. Performance comparison for the two modulation formats were done over different transmission distances. ASK also known as On-Off keying (OOK) performed better for shorter lengths whereas DPSK performed better for longer lengths of up to90km.Experimental results on a 10 Gbps NRZ- ASK signal gave a receiver sensitivity of -21.1 dBm from digital signal processing (DSP) aided receiver against -19.8 dBm from the commercial bit error ratio tester (BERT) yielding a small difference of 1.3 dB hence validating the reliability and accuracy of the digital signal processing (DSP) assisted receiver.

Traditional direct detection scheme and coherent detection scheme performances were evaluated again on a 10 Gbps NRZ ASK signal. Coherent detection that can achieve a large unamplified transmission reach and has a higher passive optical splitting ratio was first evaluated using the VPI simulation software. Simulation results gave a receiver sensitivity of -30.4 dBm for

coherent detection and -18.3 dBm for direct detection, yielding a gain in receiver sensitivity of 12.1 dB. The complex coherently detected signal, from the experimental setup gave a receiver sensitivity of -20.6 dBm with a gain in receiver sensitivity of 3.5 dBm with respect to direct detection.

A multilevel pulse amplitude modulation (4-PAM) that doubles the data rate per channel from10 Gbps to 20 Gbps by transmitting more information in the amplitude of the carrier signal was implemented. This was achieved by modulating the optical amplitude with an electrical four level amplitude shift keyed (ASK) signal. A receiver consisting of a single photodiode, three decision circuits and a decoding logic circuit was used to receive and extract the original transmitted data. A DSP aided receiver was used to evaluate the link performance. A receiver sensitivity of -12.8 dBm is attained with a dispersion penalty of about 7.2 dB after transmission through 25 km of G.652 fibre.

**List of acronyms**

| | |
|---|---|
| ADC | Analogue to digital converter |
| APD | Avalanche photodiode |
| AWGN | Additive white Gaussian noise |
| ASE | Amplified spontaneous emission |
| ASK | Amplitude shift keying |
| BER | Bit error ratio |
| BERT | Bit error ratio tester |
| CBC | Centre for Broadband Communication |
| CC | Channel capacity |
| CD | Chromatic dispersion |
| CW | Continuous wave |
| DD | Direct detection |
| DEMUX | De-multiplexer |
| DGD | Differential group delay |
| DC | Direct current |
| DCF | Dispersion compensation fibre |
| DOF | Degrees of freedom |
| DSP | Digital signal processing |
| DPSK | Differential phase shift keying modulation |
| DWDM | Dense wavelength division multiplexing |
| DQPSK | Differential quadrature phase shift keying |
| DM | Direct modulation |
| DML | Direct modulation laser |
| DP-QPSK | Dual polarization differential quadrature phase shift keying |
| EDFA | Erbium doped fibre amplifier |

| | |
|---|---|
| EAM | Electro absorption modulation |
| ED | Error detector |
| FBG | Fibre Bragg Grating |
| FTTH | Fibre to the home |
| FWM | Four wave mixing |
| FDM | Frequency division multiplexing |
| GVD | Group velocity dispersion |
| GVD | Group velocity delay |
| HOM | Higher order modulation |
| ISI | Inter symbol interference |
| IMDD | Intensity modulation direct detection |
| IMCD | Intensity modulation coherent detection |
| ITU | International telecommunication union |
| IM | Intensity modulation |
| LO | local oscillator |
| LPF | Low pass filter |
| MZDI | Mach-Zehnder delay interferometer |
| MZI | Mach-Zehnder interferometer |
| MZM | Mach-Zehnder modulator |
| MMF | Multimode fibre |
| M-PAM | Multilevel pulse amplitude modulation |
| NLSE | Non-linear Schrodinger Equation |
| NL | Non-linear |
| SPM | Self-phase modulation |
| NRZ | Non-return-to-zero |
| NZDSF | Non-zero dispersion shifted fibre |
| OSNR | Optical signal-to-noise ratio |

| | |
|---|---|
| OOK | On-Off Keying |
| PSK | Phase shift keying |
| Pol.SK | Polarization shift keying |
| PIN | Positive intrinsic negative |
| PD | Photodetectors or Photodiode |
| PMD | Polarization mode dispersion |
| PSK | Phase shift keying |
| PDF | Probability distribution functions |
| PPG | Programmable pattern generator |
| PON | Passive optical network |
| PC | Polarization controller |
| PDM | Polarization division multiplexing |
| PMF | Polarization maintaining fibre |
| PRBS | Pseudo random binary sequence |
| QAM | Quadrature amplitude modulation |
| SE | Spectral efficiency |
| RZ | Return to zero |
| SBS | Stimulated Brillouin scattering |
| SMF | Single mode fibre |
| SSMF | Standard single mode fibre |
| SRS | Stimulated Raman Scattering |
| SNR | Signal-to-noise ratio |
| TDM | Time division multiplexing |
| VOA | Variable optical attenuator |
| VCSEL | Vertical cavity surface emitting laser |
| WDM | Wavelength division multiplexing |
| XPM | Cross-phase modulation |

# Chapter 1

## 1 Introduction

The existing diverse communication systems have advanced rapidly in the last few decades to support our information driven societies and economies, thereby transforming the whole world into a global village. It is common vision that the next generation and future communication networks are all converging into an optical communication system, which will enable a wide variety of digital services such as the internet, mobile television, mobile phones, fixed telephones, video conferencing and 3D entertainment. Commercial deployment of fibres started in the 1980s only as a backbone for long haul transmission systems, but today the deployments have extended to metro and even access networks [1]. The deployment of optical fibres in all networks is meant to meet the high demand in communication throughput by finding innovative ways to increase the data carrying capacity of a single optical fibre and/or increasing the bandwidth per channel [2-4]. To achieve the goal of increasing transmission capacity in a single channel, researchers have explored and attempted to optimize on multiplexing techniques that includes time division multiplexing(TDM), wavelength division multiplexing (WDM), polarization division multiplexing (PDM) and frequency division multiplexing (FDM) [2]. Commercial systems have been deployed that utilizes all four dimensions to send more information through a single fibre than ever before [5]. Most of the deployed optical communication networks use dense wavelength division multiplexed (DWDM) systems to increase the channel capacity by transmitting different data streams on different wavelengths (channels) simultaneously using a single fibre [5-7]. Until recently, most DWDM systems within the C–band (1530-1570 nm) have been used to transmit 96 channels at 50 GHz channel spacing, conforming to the international telecommunication union (ITU) standards [8, 9]. The legacy dense wavelength division multiplexed DWDM systems operating at data rates of 10 Gbps running in today’s optical networks should be updated with more spectral efficient modulation formats to further achieve higher data rates per wavelength. Different higher order modulations formats have been studied [4, 10-12]. In the past three and a half decades, some record high capacity and high speed transmissions were recorded and are categorized into transmission generations. From the early 1980 to mid-1990s, transmission data rates of 2.5 Gbps, 5 Gbps and

10 Gbps per channel were attained using On-Off keying modulation format [8, 13]. The birth of the first generation of WDM from the mid-1990s has brought a greater expansion in the network capacity by sending multiple wavelengths, each at data rates of 10 Gbps within the same fibre achieving 32 x 10 Gbps transmission capacity [13]. The second generation of the DWDM system further increased the transmission capacity to 192 x 10 Gbps with channel spacing reduced to 25 GHz on the same On-Off keying modulated signal [8]. The third generation was driven by the introduction of electronic equipment operating at higher data rates in the tune of 40 Gbps coupled with the use of higher order modulation formats which are more spectral efficient. Combining high data rates per channel, multilevel modulation format and spectral efficiency into a DWDM system, the third generation has achieved a landmark channel capacity of 88 x 40 Gbps. More recent advances in the years 2013 to date form the fourth generation of the optical communication networks. The fourth generation operating at data rates of 100 Gbps has achieved a maximum transmission capacity of 10 Tbps (100 x 100 Gbps). Currently, research and development is now focused on working on systems that will operate at 400 Gbps per channel achieving a super channel for the fifth generation optical communication network employing advanced quadrature amplitude and phase (M-QAM) modulation techniques and coherent detection schemes[8, 13]. However these higher order modulation formats come with a trade-off between capacity and transmission reach. Fujitsu in 2011, along with a limited number of other vendors, introduced 100 G transponders and muxponders, based on single carrier dual polarization quadrature phase shift keying (DP-QPSK) modulation and coherent detection [8, 14]. A short range transmission with a capacity of 255 Tbps was demonstrated for a distance of 1 km using space multiplexing [5].

## 1.1 Motivation

The convergence of the different communication systems into an optical communication system and the recent rise in internet usage have brought about a higher demand for the available bandwidth and a need for longer unamplified transmission reach. Among the different solutions to increase capacity, deployment of new transmission systems and transmission links to support the high bit rate channels is expected to be highly costly. A sustainable way to ease the demand for bandwidth is to craft cost effective high data rate channels that will be compatible with currently deployed optical communication networks. Compatibility implies that the new channels should be able to tolerate both linear and nonlinear optical transmission impairments taking place in the transmission links. Furthermore, they should be able suit the conditions of today's transmission systems such as the channel spacing and the transmission reach.

In order to satisfy the current demand for bandwidth, higher order optical modulation formats should be exploited together with the relevant detection and performance evaluation techniques. The motivation of the work performed in this thesis can be divided into three main categories:-

- To implement a cost effective higher order modulation formats at 10 Gbaud and 20 Gbps data rate per channel and measure its performance with reference to receiver sensitivity. A spectral efficient, higher order (multilevel) signal, comprising of two bits per symbol was experimentally generated from a single programmable pattern generator (PPG) to achieve the desired transmission speed of 20 Gbps. The multilevel signal was successfully demodulated using a single photodetector making the whole design cost friendly.

- To design and implement a reconfigurable digital signal processing aided receiver to evaluate the performance of high speed optical communication systems. The digital signal processing (DSP) aided signal analyzer that was developed for the first time at the Centre for Broadband Communication (CBC) research unit, at Nelson Mandela Metropolitan University (NMMU) is quite an important tool for monitoring the quality of the signal. The tool was used to analyze the traditional two level signal in general and a higher order modulated signal in particular for there are no companies in South Africa producing the required hardware.

- To design and implement a transmission system that achieves longer unamplified transmission distances in a high speed optical communication system. Coherent detection technique that increases the transmission distance was practically implemented using the traditional cost effective 3 dB coupler as opposed to the use of more complex and expensive 90 degree optical hybrid.

The higher order modulation format with the relevant reconfigurable DSP assisted receiver and coherent detection schemes were experimentally demonstrated for the first time at the CBC at NMMU. The transmission speeds and distances demonstrated in this thesis are not to compete with the current trends and data rates in telecommunication industries but to develop compatible cost effective modulation and demodulation techniques that address the bandwidth demand by increasing the data rates per fibre while maintaining the bandwidth constant.

## 1.2 Outline of the Thesis

This thesis is organized into seven main chapters as follows:

- The first chapter will give a brief description of the evolution in channel transmission capacity of optical communication systems in the last three and half decades. The chapter will conclude with a detailed motivation of the research work.

- The second chapter opens with a brief description of some of the performance parameters used to compare different modulation formats. The second part introduces the primary digital modulation formats that are used in optical communication systems such as binary non-return to zero, amplitude shift keying (NRZ-ASK) and differential phase shift keying (DPSK). Secondary higher order modulation formats like differential quadrature phase shift keying (DQPSK) and quadrature amplitude modulation (QAM) will be discussed. For each of the modulation formats a brief explanation will be given on the generation schemes, detection schemes and the expected signal constellation diagrams. The primary modulation formats serve as the building blocks in understanding the architecture and operation of the multilevel modulation formats mentioned later in chapter six.

- The third chapter describes the linear and nonlinear transmission impairments within the optical fibre and how they degrade the signal quality during transmission. Chromatic dispersion (CD), polarization mode dispersion (PMD) and nonlinear effects are among the impairments discussed. Different optical detection techniques to include direct detection, non-coherent detection and coherent detection will be discussed. The chapter will conclude with a description of the digital signal processing techniques to evaluate the performance of a high speed optical communication system. The bits for bit and quality factor techniques are the performance evaluation methods that were developed to establish the receiver sensitivity.

- The fourth chapter gives a comparative performance between an amplitude modulation direct detection and differential phase modulated optical communication system. The chapter ends with a description of the reconfigurable digital signal processing aided receiver and its performance validation and authentication against experimental results from a commercial bit error ratio tester.

- The fifth chapter will evaluate the performance of an optical communication system with the same modulation format but different detection technologies. The optical coherent receiver will be explained in detail with emphasis on the digital signal processing (DSP) circuits that were designed to low pass filter the signal and eventually evaluate the link performance through bit error ratio (BER) computations. The chapter concludes with a comparative performance of the two detection technologies and their applicability to different optical networks.

- Chapter six will discuss a spectral efficient higher order modulation format that was experimentally demonstrated. Multilevel pulse amplitude (4-PAM) 10 Gbaud with a data rate of 20 Gbps per channel will be discussed. The generation and detection of the multilevel signal and the subsequent performance evaluation of the optical link are the main areas of discussion in this chapter.

- Chapter seven will give a comprehensive conclusion to the research work. The thesis ends with appendices and references.

# Chapter 2

# 2 General overview of an optical communication link

## 2.1 Introduction

This chapter gives a detailed overview of the entire optical communication system with emphasis on major evaluation parameters, different modulation techniques, various modulation formats and ends with an account on detection technologies. Among the evaluation parameters discussed are the receiver sensitivity, channel capacity and spectral efficiency. The universal and cost effective intensity modulation format (IM) followed by differential phase shift keying modulation (DPSK) are discussed before giving a description on more spectral efficient higher order modulation formats. Multilevel pulse amplitude modulation (M-PAM) is explained in detail in this research for it was experimentally demonstrated. Differential quadrature phase shift keying (DQPSK), Dual polarization differential quadrature phase shift keying (DP-QPSK) and quadrature amplitude (QAM) modulation are some of the higher order modulation formats that areal so highlighted. The last section of the chapter is dedicated to a discussion of the different detection technologies that were implemented to efficiently decode particular modulation formats. Direct and coherent detection methods are discussed with a polarization towards their performance capabilities on appropriate modulation formats.

## 2.2 Optical communication system overview

A basic optical communication system consists of a transmitting device (optoelectronic transmitter) that converts an electrical signal into an optical signal, the physical transmission medium (an optical fibre cable) that carries the light and a receiver (optoelectronic device) that accepts the light signal and converts it back into an electrical signal [15]. In the transmitter section, a serial bit stream in electrical form is presented to a modulator, which superimposes the data appropriately onto the optical carrier signal for transmission over the fibre to the receiver.

At the receiver end, light is applied to a photodetector which converts the light signal from optical form back to electrical form. The signal is then amplified and applied to an analogue to digital converter (ADC) circuit which isolates the individual state changes and their timing [16]. It then decodes the sequence of state changes and reconstructs the original bit stream.

There are three dominant transmission modalities being used by the telecommunication industries, the copper wire, wireless and the optical fibre. Wireless technology which has greatly replaced copper wire in most sectors is still crucial in the communication industry because of some of its conveniences such as mobility. However optical fibre stands as an enabler to wireless technology. The attraction of transmission over an optical fibre are mainly in its much larger capacity, immunity to electromagnetic interference and low loss over long transmission reach compared to copper and wireless counterparts. At present, optical fibre transmission is seen as a dominant technology for both long haul and short haul broadband data transmissions [17, 18].

## 2.3 Performance characteristics of an optical communication link

### 2.3.1 Channel Capacity (C)

The channel capacity (C) of a transmission system is the maximum rate at which bits can be reliably transferred within the optical communication link. The migration from single channel to multi-channel systems has also contributed greatly to boosting the capacity of today's optical networks. Wavelength division multiplexing (WDM), a widely deployed technology in which multiple wavelengths are used to simultaneously carry data from multiple transmitters in the same fibre [19-21].The bit rate and reliability of a transmission system are affected by the channel bandwidth, the signal power and the noise power, commonly known as signal to noise ratio [16, 22].

### 2.3.2 Channel Bandwidth ($\Delta f$)

The bandwidth of a channel is defined as the range of frequencies that a channel can reliably transmit. The Shannon sampling theorem says that, if a channel has a bandwidth,$\Delta f$, then the narrowest pulse that can be transmitted over the channel has a duration t = $1/(2\Delta f)$. The maximum rate at which pulses can be transmitted through the channel is given by: (C = $2\Delta f$.pulses). In optical communication systems, binary signal which carries one bit at a time is normally considered for simplicity. Binary signals typically have two signal amplitude levels to encode the information on. However, it is possible using higher order modulation formats to send data pulses with more than two levels. In its most general form multilevel signal pulses can be built from a set of amplitudes, phases and/or state of polarization alphabets, which will be used to transmit more bits per symbol.

By using multilevel transmission system with $M = 2^m$ levels (alphabets) we could then transmit at a channel capacity of:

$$C = m.2.\Delta f = \log_2 M.2\Delta f. \qquad [1.1]$$

where M represents the number of levels or symbols (alphabets) for a given number 'm' of binary variables (bits per symbol).

Equation 1.1 shows that the channel capacity can be increased arbitrarily by increasing the number of bits per symbol (m) or by increasing the bandwidth of the channel ($\Delta f$). However, in a practical communication link, the number of bits per symbol must be limited. The channels may get distorted if too much power is inserted and nonlinearities will set in. Alternatively the number of levels in a channel is also limited by the signal-to-noise ratio (SNR). Lastly the bandwidth of the channel cannot be increased easily [22].

Theoretically, the best multilevel encoding that can be achieved for a signal with amplitude maxima $A_S$ and a noise signal of maximum amplitude $A_N$ is given by:-

$$M = \frac{A_S}{A_N} \qquad [1.2]$$

Then the channel capacity translates to:-

$$C = m.2.\Delta f = \log_2 M.2\Delta f = \Delta f.\log_2 M^2 = \Delta f.2.\log_2 \frac{A_S}{A_N} \qquad [1.3]$$

In an optical communication system the main goal is to have a reliable link. A reliable communication system is one that achieves arbitrarily small error probabilities by using the appropriate encoding and decoding schemes. Shannon in his theorem addressed the issue of determining maximum possible achievable bit rate at which reliable communication is achievable over an ideal channel of bandwidth Δf and a given signal- to-noise-ratio (SNR).

The Shannon channel capacity theory considers that the noise distribution in the link is Gaussian. The channel capacity is therefore given by:

$$C = 2.\Delta f.\log_2[1 + \frac{S}{N}] \qquad [1.4]$$

Where $\frac{S}{N} = \frac{A_S}{A_N}$ the ratio of the signal and noise power in the channel.

The channel capacity depends on the signal power (S) and the noise signal power (N) that the link can accommodate for reliable communication [23, 24].

The signal bandwidth required for a communications channel depends on the symbol rate and not on the bit rate. In digital communication systems, symbol rate is the number of symbol changes (waveform changes or signaling events) made to the transmission medium per unit time using a digitally modulated signal. The symbol rate is measured in baud (Bd) or symbols/second. In other words, symbol rate is the ratio of the bit rate to the number of bits transmitted per symbol whereas bit rate is the frequency of a system bit stream [25, 26].

### 2.3.3 Spectral efficiency (S.E)

Another important parameter that characterizes the performance of an optical communication system is its spectral efficiency or information density. The spectral efficiency is the maximum number of bits (the channel capacity) that can be transmitted per bandwidth (Δf) of a transmission media. The spectral efficiency is mathematically defined as:

$$\mathrm{S.E} = \frac{C}{\Delta f} = \log_2\left[1 + \frac{S}{N}\right] \qquad [1.5]$$

More often the spectral efficiency is expressed as:-

$$\mathrm{S.E} = \log_2\left[1 + \frac{C.E_B}{N_0 \Delta f}\right] \qquad [1.6]$$

Where $S = C.E_B$, $E_B$ is the energy per bit and $N_0$the noise spectral density.

From equation (1.6) it is evident that the total noise changes with the channel bandwidth under consideration.

### 2.3.4 Receiver Sensitivity

An important characteristic to indicate the receiver performance in an optical transmission system is called the receiver sensitivity. It is defined as the minimum average received optical power for a given bit error ratio (BER). For example in Telecommunications the standard BER of $10^{-9}$or below is used to define the receiver sensitivity. The BER depends on the signal to noise ratio (SNR), which depends on various noise sources that degrade the received optical signal. Significant noise contributions are the amplified spontaneous emission (ASE), shot noise and thermal noise. The receiver sensitivity can be degraded due to the fibre dispersion that leads to power penalties and depends on both the bit rate and the fibre length. The performance of an optical receiver can also be measured using the eye diagram. The closing of the eye is a measure of degradation in receiver performance and is associated with a corresponding increase in the BER [6, 26].

## 2.4 Optical transmitter

An optical transmitter is an optical communication component that comprises of a laser source and signal conditioning electronics used to couple a signal into the fibre for transmission to the receiver. Semiconductor lasers that include, distributed feedback (DFB)lasers, are intensively used as optical sources because of their compatibility with the optical fibre communication channel[23, 27]. DFB lasers are also easy to modulate and are more power efficient. In the transmitter the RF electrical signal is modulated onto the light signal before injection into the fibre.

Three basic modulation technologies namely direct/internal modulation (DM), electro-absorption modulation (EAM) and Mach-Zehnder modulation (MZM)are commonly employed to modulate the light signal in most optical communication systems. New and innovative ways of implementing these existing modulation technologies give rise to novel higher order modulation formats. These modulation techniques are constantly being researched on in order to resolve the future requirements of high spectral efficient and high bit rate dense wavelength division multiplexing (DWDM) optical networks [28, 29].

### 2.4.1 Modulator technologies

#### 2.4.1.1 Internal modulation or directly modulated lasers

Direct modulation (DM) is the easiest and most cost effective way to impose data on an optical carrier. In a directly modulated system an offset current is applied to the laser diode, such that the laser is above the lasing threshold. The transmitted data is modulated onto the laser drive current, which then switches the optical signal between the 'On' and 'Off' states depending on the logic state of the input data signal [6, 22]. Figure 2.1 shows how the input electrical data is directly modulating the laser.

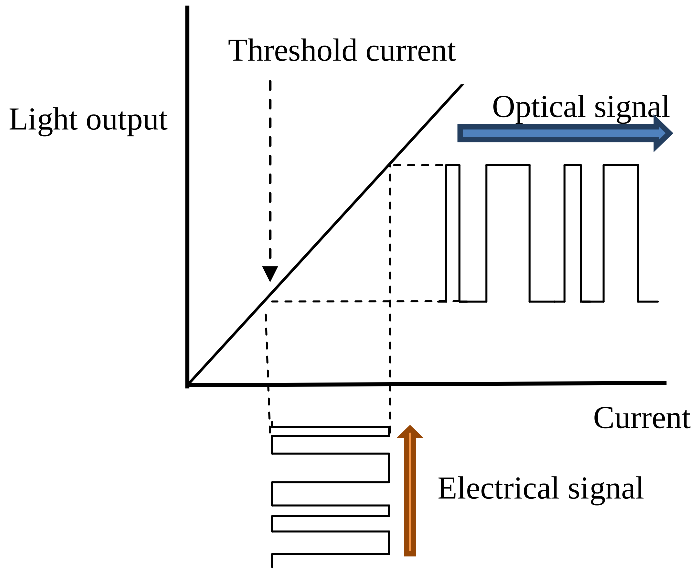


Figure 2.1: Transfer curve of a directly modulated laser

The resulting modulation format is binary intensity modulation. However, directly modulated lasers have limited signal quality. The compromised quality is due to strong modulations of electrical carriers within the laser that leads to severe distortions on the signal amplitude and phase [30, 31]. Direct intensity modulation leads to some variation of carrier concentration in the laser active region, that greatly affects the refractive index and in turn the frequency of a generated optical signal. Thus, the internal laser modulation leads to undesired frequency chirping.The chirp of single frequency laser may be described by the adiabatic chirping coefficient which is proportional to the output laser power and the transient chirping which is proportional to the logarithm of the laser power as depicted in equation 1.7 [32].

$$\Delta v(t) = \frac{\alpha}{4\pi} . \frac{d}{dt}[In(P_L(t) + kP_L(t)] \quad [1.7]$$

where $\Delta v(t)$ is the instantaneous frequency deviation, $\alpha$is the line enhancement factor, $k$ is the coefficient of adiabatic chirp and $P_L$ is the laser output power [32].

Recent advances have made possible directly modulated lasers at bit rates up to 10 Gbps and in research up to 40 Gbps [6, 33]. In this research, simulation and experimental results are presented in which a directly modulated DFB laser at 1550 nm is used. Figure 2.2 is a picture for an internally modulated, DFB laser that was used in our experimental work and its conditioning electronics connections.

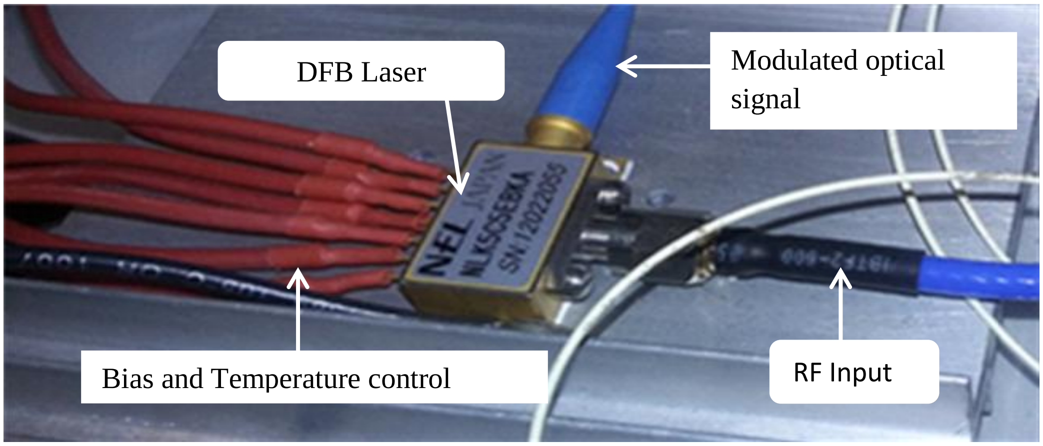


Figure 2.2: Internally modulated DFB laser [NLK5C5EBKA] used in our work.

#### 2.4.1.2 External modulation

##### 2.4.1.2.1 Electro-absorption modulators

An electro-absorption modulator (EAM) consists of a semiconductor material which controls the intensity of a laser beam through an applied external electric voltage as shown in figure 2.3.

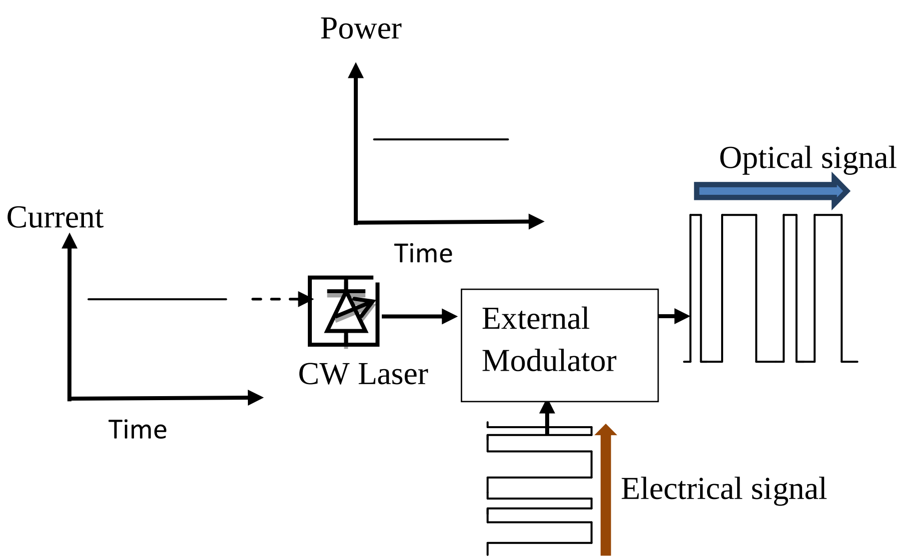


Figure 2.3: An external electro-absorption modulator system

Its operational principle i.e. the Franz–Keldysh effect is based on the change of the absorption spectrum caused by an applied electric field. EAMs features relatively low drive voltages and are cost effective to produce. These modulators are used for high speed modulation rates of up to 40 Gbps, with some research demonstrations up to 80 Gbps [30]. However, similar to DMLs they exhibit some residual chirping. They also exhibit wavelength dependent absorption characteristics and their dynamic extinction ratios do not typically exceed 10 dB [30].

#### 2.4.1.2.2 Mach–Zehnder modulators (MZMs)

A Mach-Zehnder modulator (MZM) is used for controlling the amplitude and/or the phase of an optical wave. Unlike electro-absorption modulators, Mach-Zehnder (MZ) modulators work on the principle of interference. The schematic diagram in figure 2.4 shows the MZ modulator structure.

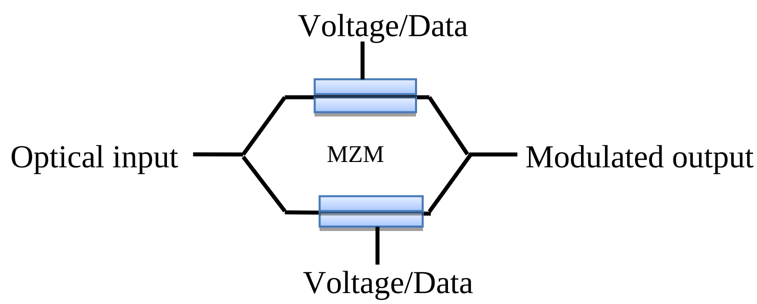


Figure 2.4: Mach-Zehnder modulator structure

The incoming waveguide is split up into two waveguide interferometer arms. In one arm an external voltage is applied to an opto-electronic material such as Lithium Niobate that introduces a phase shift to the light signal passing through it. At the output coupler, the two signals will interfere constructively or destructively in response to voltage levels of the modulating signal.

The phase shift induced in the upper arm of the interferometer depends on the refractive index of the opto-electronic material, which itself depends on the applied external electric field. When a time dependent voltage V(t) is applied across the upper waveguide of the modulator, its refractive index will become time dependent and in turn the power transmission function [$P_{out}/P_{in}$] of the Mach-Zehnder interferometer will also be time dependent as shown in figure 2.5

Assuming equal power splitting and combining ratio of the couplers of the Mach-Zehnder interferometer, the power at the output depends on the difference between the phase shifts experienced by the light propagating in the upper and lower arm of the structure. These two fields interfere at an output coupler. Applied electrical voltage controls destructive or constructive interference, thereby producing intensity modulation and/or phase modulation. The power transfer function is given by:

$$P_{out} = P_{in} \cos^2 \frac{\Delta\varphi}{2} \qquad [1.8]$$

Where $\frac{\Delta\varphi}{2}$ is the phase difference between the upper and lower arm of the interferometer

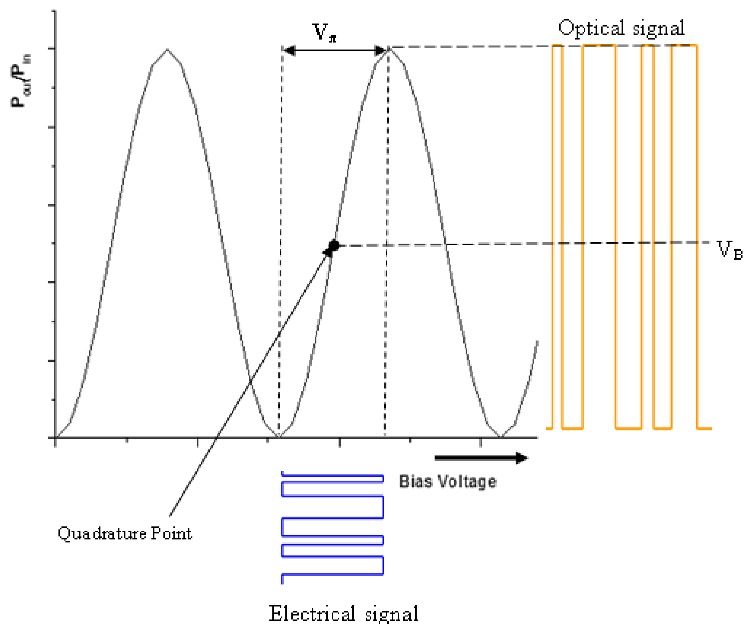


Figure 2.5: Transfer function for the MZ modulator and operation condition for a NRZ modulation format

Due to their good modulation performance and the possibility of independently modulating intensity and phase of the optical field, many advanced optical modulation formats are based on using these MZMs [22, 34]. They can be driven in different ways to generate a variety of important modulation formats. MZM modulator produces a high quality signal, especially when the continuous wave signal from the laser is first guided into a preconditioning device such as a pulse carver modulator which is responsible for shaping the return to zero (RZ) pulses which are more robust to inter symbol interference (ISI) than their equivalent non return to zero (NRZ) pulses. These kind of transmitters are almost uniquely used for ultra-long haul and high speed (40 Gbps and higher) communication systems [30].

## 2.5 Digital optical data modulation formats

There exist a variety of digital modulation formats that have been implemented and researched on up to date [10, 35-40]. The main target in the design of an optical communication link is to investigate candidate optical modulation formats capable of achieving higher spectral efficiencies (SE) and eventually quality higher transmission capacities at an affordable cost to meet the requirements of a particular network [1].

Modulation is a technique by which the digital information is printed or inscribed or superimposed onto an optical carrier and in its most general sense also includes coding to prevent transmission errors [41, 42]. In optical communication systems, electromagnetic waves with frequencies of nearly 200 THz are used to transfer information from one point to another [37, 42]. An optical signal is fully characterized by its amplitude, frequency (wavelength), phase and its polarization state.

The electric field of an optical signal is popularly represented in two different ways, the complex notation and rectangular notation respectively:

$$E(t) = \hat{e}Ae^{-j\left(\omega t+\frac{2\pi i}{M}\right)} \quad [1.9]$$

$$E(t) = A.\cos\left(\omega t + \frac{2\pi i}{M}\right) \quad [1.10]$$

where A is the amplitude, $\omega$ is the frequency, $\theta = \frac{2\pi i}{M}$ is the initial phase and $\hat{e}$ represents the state of polarization. M stands for the number of symbols and i =1: M.

In coming up with a variety of modulation formats, there are only three scalar parameters and a vector to modulate. The different modulation formats are named after the parameter of the laser signal being modified. These can be classified as:

- Amplitude shift keying (ASK) modulation [43-45]
- Phase shift keying (PSK) modulation [46]
- Frequency shift keying (FSK) modulation
- Polarization shift keying (PolSK) modulation [11, 47]

The schematic diagrams in figure 2.6 shows how the optical signal is modulated by a ‘01010011’ electrical bit stream for the different modulation formats mentioned above [6, 22].

Other advanced modulation formats such as multilevel pulse amplitude modulation (PAM), differential quadrature phase shift keying (DQPSK), dual polarization differential quadrature phase shift keying (DP-QPSK)and amplitude quadrature modulation (AQM) formats have higher spectral efficiencies than the standard binary modulation since they transmit more information in the amplitude, phase, polarization and/or a combination of both amplitude and phase. However all the different modulation formats are developed from the three basic modulation technologies highlighted above.

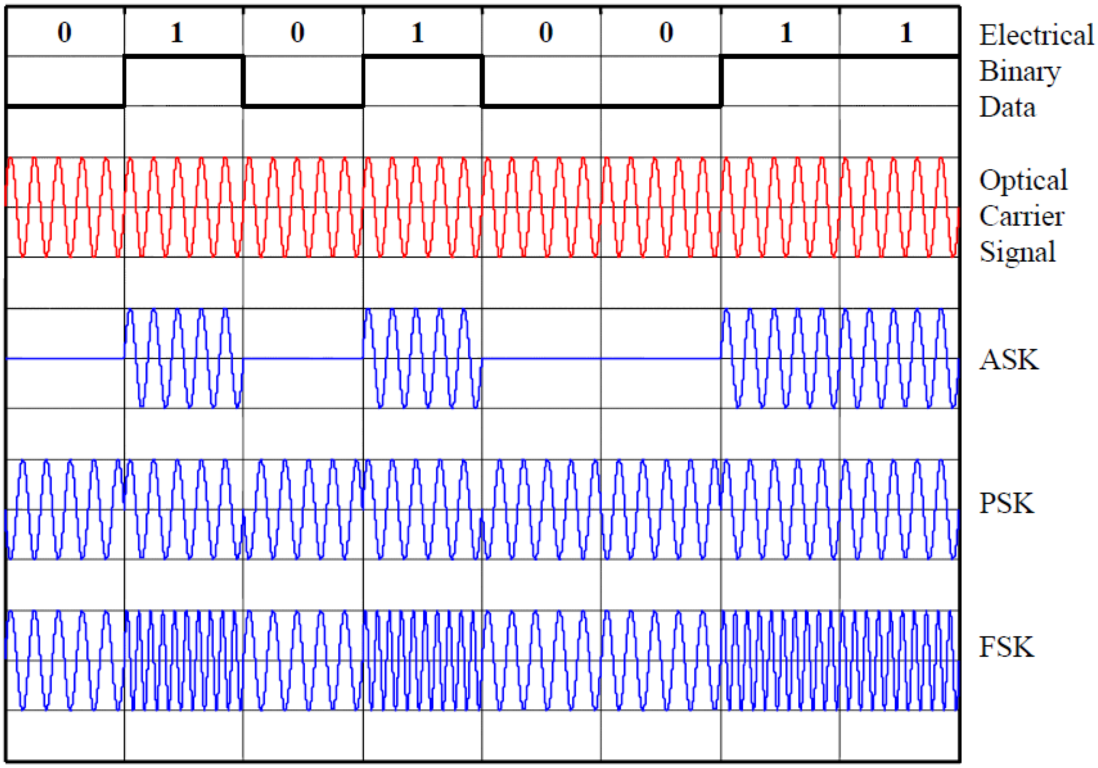


Figure 2.6: An electrical binary data stream “01010011” used to modulate the amplitude, phase, and frequency of an optical carrier signal. [ASK,PSK and FSK] respectively [6]

### 2.5.1 Amplitude shift keying (ASK) modulation

Amplitude shift keying (ASK) signal can be generated using either a directly modulated laser, an electro-absorption modulator or a Mach-Zehnder modulator (MZM) [48, 49]. Directly modulated lasers and electro-absorption modulators provide a cost effective solution and require less electrical power to drive the signals feeding the optical modulator compared to the MZM. However, the fact that they usually introduce some chirp into the signal makes them less suitable for long-haul transmission [1].

Amplitude shift keying (ASK) also known as binary intensity modulation (IM) is the commonly used modulation format in the deployed optical transmission systems available today [34, 36]. It is the simplest digital modulation technique where the digital information signal directly modulates the amplitude of an analog optical carrier. Amplitude shift keyed signal can be expressed as:

$$V_{ASK} = \frac{A}{2}[1 + V_m(t)]cos(\omega_c t) \quad [1.11]$$

where $V_{ASK}$ is the amplitude modulated signal, A is the amplitude, $V_m(t)$ is the modulating signal, t is the time and $\omega_c$ is the frequency of the carrier signal.

The modulating signal [$v_m(t)$] is a normalized binary waveform, taking values of +1 V for logic '1' and -1 V for logic '0'.The modulated wave $V_{ASK}(t)$, is either $A\cos(\omega_c t)$ or zero. The carrier is either 'ON' or 'OFF' which is why amplitude shift keying (ASK) is sometimes referred to as On-Off Keying (OOK) as shown in figure 2.6.This can be achieved by directly modulating the current of the laser source as shown in figure 2.1 or by using an external optical modulator to modulate the amplitude of the laser carrier signal, figure 2.3. On-Off keying can also be obtained by properly bias a MZM and it swings within $V_\pi$ voltage range as shown in figure 2.5 yielding a constellation plot shown in figure 2.7. The constellation plot shows two points corresponding to the one and zero bits for an ON OFF modulation format.

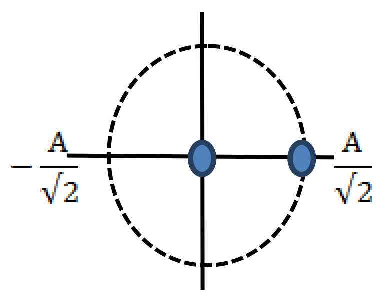


Figure 2.7: OOK constellation diagram [1]

To date most optical communication systems use the binary amplitude shift keying(ASK) modulation format mainly because it is simple and cost effective to implement. However due to increase in demand for bandwidth, advanced modulation formats with improved performance compared to binary modulations are the potential candidates to meet the ever increasing communication demand [33, 35, 49, 50].

### 2.5.2 Differential phase shift keying (DPSK) modulation

In intensity modulation, digital signals are represented by instantaneous optical power levels. Digital signals can also be represented by the phase of an optical carrier and this is commonly referred to optical phase shift keying (PSK). Differential phase shift keying (DPSK) modulation format is a promising technique to improve the performance of an optical communication systems[6, 35,51]. The main benefits of DPSK signals when compared to the conventional ASK format is the high receiver sensitivity due to the 3dB reduction in optical signal to noise ratio (OSNR), the extended unamplified transmission reach, reduced optical power requirements and the relaxed component specifications [6, 22, 34].

In phase shift keying (PSK), bit streams are encoded into the phase of the optical carrier signal, while the amplitude and the frequency are kept constant. For binary phase shift keying (BPSK) formats, the phase takes two values, commonly chosen to be 0 and π. Phase modulated signal can be generated using a Lithium Niobate electro-optic crystal, embedded in a MZI structure.

The phase shift induced by the Lithium Niobate crystal is proportional to the refractive index change and is linearly dependent on the applied voltage V(t). The input-output relationship of such a phase modulator can therefore be simply expressed as:-

$$E_{out} = E_{in} \exp - [j \frac{\pi}{V_\pi} V(t)] \quad [1.12]$$

where V(t) is the applied external voltage and $V_\pi$ is the peak to peak voltage of the electrical signal also known as the driving voltage.

The phase modulated optical signal has a constant power envelope. Figure 2.8 show how a MZM is biased at the minimum transmission voltage, point to produce a DPSK modulated signal. Bipolar biasing gives an electrical driving signal with an amplitude equivalent to 2Vπ as it swings between the two crest points of the MZM structure [1].

Achieving phase modulation is not practically straightforward, especially for digital signals, since the phase modulated signal is not easily visible, like an intensity modulated signal that can be easily monitored on an oscilloscope following detection by a photodiode. Figure 2.9 shows the constellation plots for a DPSK signal. It is evident on comparing figures 2.7 and 2.9, that the DPSK constellation points are further apart by a factor of two which when translated to power results in a 3 dB sensitivity improvement for DPSK.

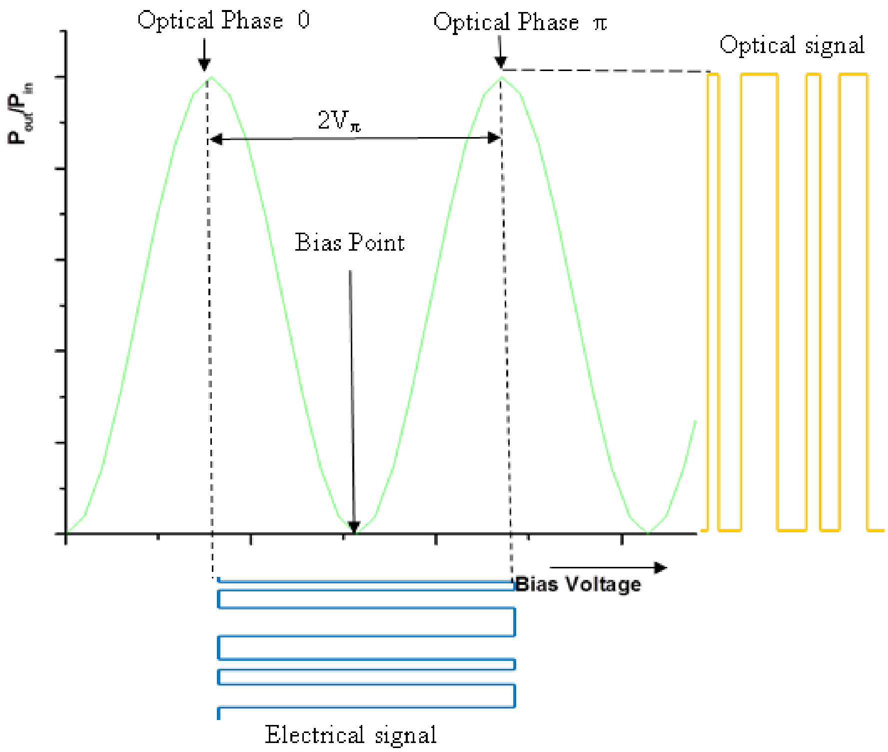


Figure 2.8: Driving a MZM using a binary electrical signal with amplitude of 2Vπ to generate a DPSK signal [35]

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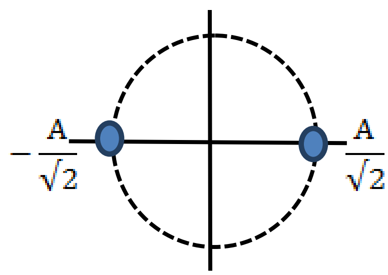


Figure 2.9: DPSK constellation diagram [35]

However the improved sensitivity comes with increased cost and complexity when it comes to practical implementation due to additional components required at the transmitter and receiver side [6]. A pre-coder circuit is required at the transmitter and a delay interferometer (DI) is required at the receiver. The additional components are called for since the photodetector we have on the market cannot directly detect the absolute phase of the signal. There is a need to modify the signal prior to transmission and then perform a phase to intensity conversion in order to demodulate the transmitted signal.

A standard DPSK transmission link consists of a continuous wave (CW) laser source, a pre-coder circuit, a DPSK optical modulator which encodes the data into the phase of the optical signal and a DPSK receiver which demodulates the received data as shown in figure 2.10 [6, 52].

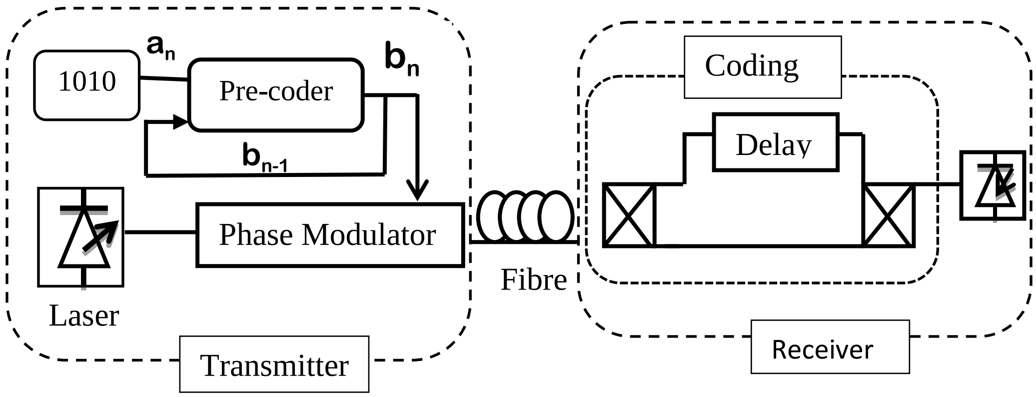


Figure 2.10: Schematic diagram of an optical DPSK transmission setup

A detailed description of each of the components is given in the following sections of this thesis.

### 2.5.2.1 DPSK pre-coder and transmitter

In DPSK the initial information sequence to be transmitted is first transformed into a new pre-coded sequence. The new sequence often referred to as differentially pre-coded sequence, is obtained by coding information into the phase difference between two adjacent symbols.

Table 2.1: Truth table for an XOR logic gate

| $b_{n-1}$ | $a_n$ | $b_n$ | $\Delta\theta$ |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 1 | 1 | $\pi$ |
| 1 | 0 | 1 | $\pi$ |
| 1 | 1 | 0 | 0 |

As shown in figure 2.10 the data to be transmitted $a_n$ is first differentially encoded into a new sequence $b_n$, which is then used to drive the phase modulator. Table 2.1 is the truth table for the differential encoder, showing all the possible phase difference combinations between any two adjacent bits. There is no phase change on transmitting a “0” bit, while there is a ‘π’ phase change on sending a ‘1’ bit on the pre-coded bit stream $b_n$ [6, 52]. The pre-coder differentially encodes the original binary bit sequence using a logic XOR gate with a feedback tap with one bit delay. It is evident from the truth table, table 2.1, that the output data from the pre-coder is high only if the two inputs ($a_n$ and $b_{n-1}$) are not the same. This means there is a π phase change when the two adjacent bits are not the same. The pre-coding logic function is best described by the following inequality digital logic function:-

$$b_n = a_n \oplus b_{n-1} \qquad [1.13]$$

where $a_n$ = [0,1] is the original transmitted data, $b_n$ = [0,1] is the pre-coded data sequence and $\oplus$ is the XOR logic function.

The encoded data is then transmitted as a bipolar signal, where $b_n$= [-1,1] as shown on the biasing of the MZM structure in figure 2.8. Figure 2.11 shows the logic circuit for an XOR gate that can be implemented as the pre-coder circuit to match all the possible phase differences shown in table 2.1.

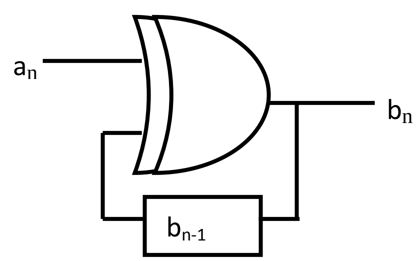


Figure 2.11: Logic circuit for the XOR function

### 2.5.2.2 DPSK decoder

In a normal PSK modulation format, the demodulation is implemented in a complex coherent receiver that uses a local oscillator (LO) laser as a reference signal. In the case of DPSK the demodulation is possible without the requirement of using a local oscillator. Instead of the LO signal, the incoming signal is mixed with a delayed replica of itself, resulting in a self-homodyne differential demodulation scheme also known as interferometric detection. In this scheme, the received signal is made to beat with a delayed version of itself in a photodiode. This is equivalent to performing phase to intensity modulation (PM-to-IM) conversion in an interferometer prior to direct detection in the photodiode [34, 53-55].

. The critical component of the DPSK receiver is the Mach-Zehnder delay interferometer (MZDI) which demodulates the transmitted data. Figure 2.12 shows the schematic diagram of DPSK, self-homodyne receiver based on Mach-Zehnder structure. In a self-homodyne MZDI the incoming DPSK signal is split into two identical signals. A propagation delay time equivalent to one bit period is introduced between the two paths before the two light signals propagating in each of the paths recombine in an output 3 dB coupler as illustrated in figure 2.12.

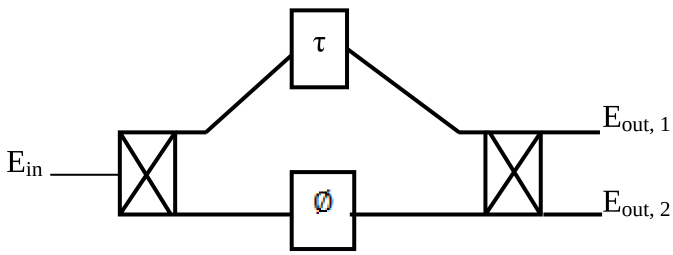


Figure 2.12: Schematic diagrams for a MZDI to be used in a self-homodyne receiver

Assuming that the two 3 dB couplers in the MZDI structure are ideal, the electric field at the two outputs couplers can be expressed as:-

$$E_{out,1}(t) = \frac{1}{2}\left[E_{in}(t-\tau) - E_{in}(t)e^{-j\emptyset}\right] \quad [1.14]$$

and

$$E_{out,2}(t) = -j\frac{1}{2}\left[E_{in}(t-\tau) + E_{in}(t)e^{-j\emptyset}\right] \quad [1.15]$$

Considering that the two split signals maintain the same state of polarization, the modulus of the electric field is given as:-

$$|E_{out,1}(t)|^2 = \frac{1}{4}\left[|E_{in}(t-\tau)|^2 + |E_{in}(t)|^2 - 2\mathrm{Re}\left\{E_{in}(t)E_{in}^{*}e^{-j\emptyset}\right\}\right] \quad [1.16]$$

$$\left|E_{out,2}(t)\right|^2 = \frac{1}{4}\left[|E_{in}(t-\tau)|^2 + |E_{in}(t)|^2 + 2\mathrm{Re}\left\{E_{in}(t)E_{in}^{*}e^{-j\emptyset}\right\}\right] \quad [1.17]$$

The input electric field is generally expressed as:-

$$E_{in}(t) = \mathrm{Re}\left\{\sqrt{P_{in}(t)}e^{-j\emptyset(t)}e^{-j\omega t}\right\} \quad [1.18]$$

The power at the output of the MZDI is therefore:-

$$P_{out,1}(t) = \frac{1}{4}\left[P_{in}(t) + P_{in}(t-\tau) - 2\sqrt{P_{in}(t)P_{in}(t-\tau)}.\cos(\theta(t-\tau) + \theta(t) - \emptyset - \omega_0\tau)\right] \quad [1.19]$$

In phase modulation the signal envelope power is constant, hence $P_{in}(t) = P_{in}(t-\tau) = P_0$. It is noted that in a practical MZDI the delay $\tau = \mathrm{T}$, the bit period and $\emptyset - \omega_0\mathrm{T} = 2\pi\mathrm{K}$. Therefore the powers from the two output ports of the MZDI structure are referred to as constructive and destructive outputs. The powers are given in two expressions below.

$$P_{out,1} = P_0 \sin^2\left[\frac{\theta(t-T)-\theta(t)}{2}\right] \quad [1.20]$$

$$P_{out,2} = P_0 \cos^2\left[\frac{\theta(t-T)-\theta(t)}{2}\right] \quad [1.21]$$

where $\theta(t-T) - \theta(t)$ is the phase difference between the two neighboring bits.

After the MZDI structure, direct detection can be achieved by using a single photodiode (single ended detection) to recover the signal by detecting it at one of the interferometer output ports or by using two photoreceivers (balanced detection) to receive the signal by detecting the difference between the constructive and destructive interferometer output ports [52, 53, 56].

The operation of a DPSK system with interferometric detection is illustrated by transmitting an input sequence $a_n$ = [01010011]. The modulation and demodulation processes on the bit sequence are considered in Table 2.2. The original bit pattern is recovered after differentially encoding, phase modulating and interferometrically detecting it. The MZDI, which enables the demodulation of DPSK signals by converting the phase difference information between consecutive bits into an intensity modulated signal, is therefore a key component for this type of a system. For differential encoding a reference bit is required to initialize the encoding process. This reference bit could arbitrarily be set to logic ‘1’ or logic ‘0’. In the table the reference bit $b_n$ at instant $n = -1$ was set to logic ‘0’.

Table 2.2: Transmitted and recovered bits in a DPSK system [6]

| Time instant n | -1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Transmitted bits $a_n$ | | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 |
| Differential encoded data $b_n$ | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| Bipolar encoder | -1 | -1 | 1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 |
| I/P Voltage MZM +/- $V_\pi$ | $-V_\pi$ | $-V_\pi$ | $V_\pi$ | $V_\pi$ | $-V_\pi$ | $-V_\pi$ | $-V_\pi$ | $V_\pi$ | $-V_\pi$ | $V_\pi$ |
| O/P electrical Field +/- E | +E | +E | -E | -E | +E | +E | +E | -E | +E | -E |
| Transmitted phase $\theta$ | 0 | 0 | $\pi$ | $\pi$ | 0 | 0 | 0 | $\pi$ | 0 | $\pi$ |
| Phase difference $\lvert\theta\rvert$ | | 0 | $\pi$ | 0 | $\pi$ | 0 | 0 | $\pi$ | $\pi$ | $\pi$ |

## 2.6 High order modulation formats (HOM)

The amount of traffic carried on optical communication networks has been growing exponentially over the past two decades. To meet the ever increasing communication requirements, the only cost effective solution might be the deployment of higher order modulation formats which are more spectral efficient and makes better use of the capacity of currently existing fiber infrastructure. Higher order modulation formats (HOM) coupled with dense wavelength division multiplexing (DWDM) are an alternative in advancing to higher data rates [29, 57, 58]. All the different higher order modulation formats implemented to date are a result of manipulating the basis amplitude or phase or a combination of both amplitude and phase modulation techniques [1, 29, 59,60].

Higher order modulation (HOM) formats are generally known as M-ary modulation schemes since data can be encoded in the M-possible alphabet symbols available to transmit the data. The word M-ary is used in analogy to the terms binary, ternary, quaternary etc. Typically the data may be encoded on the amplitude, phase and/or amplitude of the optical carrier signal. Every signal with $M = 2^m$ levels can encode a word of ‘m’ bits per symbol. Among the higher order modulation formats are the multilevel pulse amplitude modulation (M-PAM), differential quadrature phase shift keying (DQPSK), Dual polarization differential quadrature phase shift keying (DP-DQPSK) and the quadrature amplitude modulation (QAM), which combines phase and amplitude in one scheme [10, 30, 61]. An M-PAM higher order modulation format was chosen and was experimentally demonstrated in this research due to the availability of relevant hardware at the NMMU Centre for Broadband Communication (CBC) research unit and the potential of the modulation format to be integrated into the already existing optical communication structures.

### 2.6.1 Multilevel ASK

Multilevel amplitude shift keying (ASK) commonly known as M-level pulse amplitude modulation (M-PAM), where M refers to the number of levels in the signal, is a way of coding more than one bit per amplitude symbol. There is need to map the bits into symbols. The mapping between binary 'm' bits values and the "M' levels is arbitrary. A popular coding scheme is the Gray code, where the mapping rule is that every adjacent symbol differs from its neighbors by a single bit of lowest possible weight [55, 57, 62].

In recent years, 4-PAM modulation of direct modulated sources has achieved transmission rate from 10 Gbps to 40 Gbps [36, 63,64]. It was reported in 2013, that a 50 Gbps signal from the VCSEL was polarization multiplexed to a total capacity of 100 Gbps using a symbol rate of only 25 Gbaud [28]. In this research a transmission speed of 20 Gbps was obtained from a 4-PAM, 2 x 10Gbps electrical signals. The main purpose of the experiments demonstrated in this work is not to focus on transmission speeds, but on finding cost effective modulation formats with a higher spectral efficiency that can achieve higher data rates but maintaining the channel bandwidth of already deployed high speed optical communication networks.

## 2.7 Optical receivers

Photodetectors are the back bone of any optical communication system receiver for they convert the pass band optical signal back to the baseband electrical signal. In an optical receiver, the incoming modulated signal is filtered, amplified, and then applied to the demodulator and decoder circuits, which extract the original source information. A good optical communication system has higher fidelity, in that the send signal is received with the minimum possible errors [65]. The backend of the optical receiver comprises of the photodiode. The photodiode converts the optical signal back to the electrical form. There are mainly two types of photodiodes, the positive intrinsic negative (PIN) photodiode and the avalanche photodiode (APD), which are used extensively in optical communication systems. To meet the ever increasing transmission speed requirements a photoreceiver with high bandwidth and higher sensitivity is required [65-67].

In most deployed optical communication networks, two detection technologies, direct and coherent detection are normally used to demodulate the transmitted signal depending on the modulation type implemented.

### 2.7.1 Detection technologies

The migration from the traditional ASK modulation formats to higher order modulation formats in an attempt to address the rise in demand for communication requirements comes with greater complexity and increased cost at the receiver side. The direct detection technique, which is insensitive to the state of polarization of the light signal is limited to demodulating only the intensity of the incoming signal, its utility is therefore restricted to one ASK modulation format [24, 68]. Consequently, optical coherent detection is currently a detection technique of choice for it is capable of detecting any modulation format and providing a significant improvement in the detection sensitivity over direct detection receivers [54, 56, 57, 69].

#### 2.7.1.1 Direct detection

Signal intensities are detected with photodetectors (PDs). The physical process behind PDs is the absorption of light with certain quantum efficiency. Each time a photon is absorbed, an electron-hole current is generated under the influence of an electrical field that is generated from the applied voltage. In this way a photocurrent ($I_P$)is generated. The generated photocurrent is proportional to the incident optical power ($P_{in}$).

The electric field of an optical signal is defined as:-

$$E_{(s)}(t) = E_0 \cos(\omega t + \varphi) \quad [1.22]$$

with $E_0$ is the amplitude and $\varphi$ the initial phase of the signal.

Photodetectors are square law detectors [22].They convert the incident optical power ($P_{in}$) into an electric current and they convert the incident electric field by a square law into an electrical power.

In a direct detection scheme, the detected photocurrent $I_p$ is given by:

$$I_p = \Re . P_{in} = \Re . A_{eff} . \frac{1}{2}\sqrt{\frac{\varepsilon\varepsilon_0}{\mu\mu_0}} . E_0^2 = K . E_0^2 \qquad [1.23]$$

The electrical power generated in the detector with the Ohmic resistor is then given by [67]:

$$P_{el} = R . I_p^2 = R . (\Re P_{in})^2 \qquad [1.24]$$

Where R is the resistance and $\Re$ is the receiver responsivity, $\varepsilon$ electrical permittivity and $\mu$ is the carrier mobility.

It is clear from the above equation that the directly detected power only carries information about the intensity/amplitude of the signal and has no information about the phase and/or state of polarization of the received signal. This makes direct detection to be restricted to only On-Off modulation format.

#### 2.7.1.2 Coherent detection

The benefits of coherent detection schemes have been exploited on demodulating higher order modulation formats [12, 48]. Digital coherent receivers with data rates of up to 100 Gbps and beyond based on dual-polarization quaternary phase shift keying (DP-QPSK) and digital signal processing (DSP) have become a reality [70-72].

The basic idea of a coherent detector is to mix the received signal coherently with another continuous optical wave signal before directing it in a photodetector. The continuous optical wave is generated locally at the receiver by using a narrow linewidth laser, known as a local oscillator (LO).The optical field of the modulated signal is expressed as:

$$E_S(t) = E_S \cos(\omega_S t + \varphi_S) \qquad [1.25]$$

The optical field associated with the local oscillator is given by:

$$E_{LO}(t) = E_{LO} \cos(\omega_{LO} t + \varphi_{LO}) \qquad [1.26]$$

where $E_S$, $E_{LO}$, $\omega_s$, $\omega_{LO}$; $\varphi_s$ and $\varphi_{LO}$ are the amplitude, the frequency and the phase of the transmitted and local oscillator optical signals respectively.

Assuming that the two fields have identical polarizations, the photodetector measures the total field, which is the resultant field of the modulated signal and the local oscillator after mixing, and is given by : $|E_S + E_{LO}|^2$.

The final expression for the photocurrent for a coherently detected signal has three parts:-

$$I_p = K.\left\{\begin{matrix}\left[\overbrace{\frac{1}{2}|E_S|^2 + \frac{1}{2}|E_S|^2}^{D.C\ Component}\right] \\ + \\ \left[\overbrace{\frac{1}{2}E_S^2.cos(2\omega_S + 2\varphi_S) + \frac{1}{2}E_{LO}^2 cos(2\omega_{LO} + 2\varphi_{LO}) + E_S E_{LO} cos((\omega_s + \omega_{lo}) + \varphi_s + \varphi_{lo})}^{High\ frequency\ term}\right] \\ + \\ \left[\overbrace{E_S E_{LO}.cos[(\omega_S - \omega_{LO}) + \varphi_S + \varphi_{lo}]}^{Beating\ term}\right]\end{matrix}\right\} \quad [1.27]$$

The high frequency components should be filtered out since they are beyond the frequency response of the detector. We are left with the constant DC component term and the beating term.

A more convenient form is obtained, when converting the field amplitudes back into signal powers. This then leads us to.

$$I_p = \Re.\left(P_S + P_{LO} + 2\sqrt{P_S P_{LO}}.cos([\omega_s - \omega_{LO}] + [\varphi_S + \varphi_{LO}])\right) \quad [1.28]$$

Considering only the AC-coupled output of the photodiode and assuming that $P_{LO} >> P_s$, the above equation simplifies to:-

$$I_p = 2R\sqrt{P_S P_{LO}}.[cos(\omega_{IF} t + \theta_s - \theta_{LO})] \quad [1.29]$$

From equation 1.29, the advantages of using a coherent detection scheme are clearly seen and the signal information can be retrieved from the amplitude ($P_s$), frequency ($\omega_s$) or phase ($\varphi_s$) of the optical signal [34, 73]. Depending on the frequency offset between the received signal and optical signal from the LO, coherent detection can be implemented in two flavors known as homodyne and heterodyne schemes[67]. In homodyne coherent detection, the intermediate frequency is given by $\omega_{IF} = \omega_S - \omega_{LO} = 0$. For a heterodyne coherent detection scheme, the intermediate frequency is not equals zero ( $\omega_{IF} = \omega_S - \omega_{LO} \neq 0$).

### 2.7.1.3 Coherent detection with an optical hybrid

Optical equipment manufacturing companies have designed a passive optical receiver that can demodulate data capacity beyond the legacy universal On-Off system. An optical hybrid receiver which is compatible with higher order modulation formats is a candidate for demodulating the current high data rates and is a potential candidate for the next generation high speed optical communication networks [74]. An optical hybrid is in principle a six-port device (two inputs and four outputs) consisting of linear dividers and combiners interconnected in such a way that four different vector additions of a reference local oscillator (LO) signal and the signal to be detected are obtained [74]. The levels of the four output signals are detected by balanced photoreceivers. Applying suitable baseband digital signal processing algorithms, the amplitude and phase of the unknown signal can be determined[58].The schematic diagram for an optical hybrid receiver that can be used in a coherent detection setup is shown in figure 2.13.

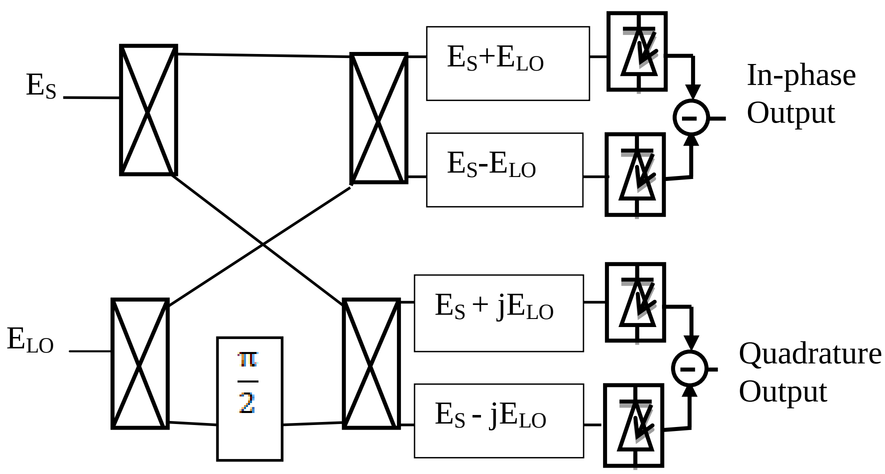


Figure 2.13: 90 degree optical hybrid receiver for coherent detection setups

The four detectors are arranged to detect and demodulate the complex quadrature signal in a balanced detection setup[52]. The in-phase detectors will output:-

$$I_{P+} = |E_S + E_{LO}|^2 \quad [1.30]$$

$$I_{P-} = |E_S - E_{LO}|^2 \quad [1.31]$$

On the other hand the quadrature detectors will output**:-**

$$Q_{P+} = |E_S + jE_{LO}|^2 \quad [1.32]$$

$$Q_{P-} = |E_S - jE_{LO}|^2 \quad [1.33]$$

The generated photocurrents are similar to the one deduced in equation [1.28] and are independently given as:

$$I_{P+} = \Re.\left(P_S + P_{LO} + 2\sqrt{P_S P_{LO}}.\cos([\omega_s - \omega_{LO}] + [\varphi_S - \varphi_{LO}])\right) \quad [1.34]$$

$$I_{P-} = \Re.\left(P_S + P_{LO} - 2\sqrt{P_S P_{LO}}.\cos([\omega_s - \omega_{LO}] + [\varphi_S - \varphi_{LO}])\right) \quad [1.35]$$

$$Q_{P+} = \Re.\left(P_S + P_{LO} + 2\sqrt{P_S P_{LO}}.\sin([\omega_s - \omega_{LO}] + [\varphi_S - \varphi_{LO}])\right) \quad [1.36]$$

$$Q_{P-} = \Re.\left(P_S + P_{LO} - 2\sqrt{P_S P_{LO}}.\sin([\omega_s - \omega_{LO}] + [\varphi_S - \varphi_{LO}])\right) \quad [1.37]$$

Balanced detection comes with the benefit of passively amplifying the signal as seen upon subtracting equation [1.34] from [1.35] and [1.36] from [1.37], reproducing the in phase and quadrature components of the transmitted signal.

$$I_P = \Re.\left(P_S + P_{LO} + 4\sqrt{P_S P_{LO}}.cos([\varphi_S - \varphi_{LO}])\right) \quad [1.38]$$

$$Q_P = \Re.\left(P_S + P_{LO} + 4\sqrt{P_S P_{LO}}.sin([\varphi_S - \varphi_{LO}])\right) \quad [1.39]$$

The detected photocurrents from the three detection modalities, direct detection, single photodiode coherent detection and balanced coherent detection are detailed below considering only the AC components.

Direct detection: $$I_p = R.\sqrt{P_S}.\cos\omega t \quad [1.40]$$

Single photodiode coherent detection: $$I_{(p)} = 2R\sqrt{P_S P_{LO}}.[\cos(\omega_{IF} t + \theta_s - \theta_{LO})] \quad [1.41]$$

Balanced coherent detection: $$I_P = \left(4R\sqrt{P_S P_{LO}}.cos([\omega_{IF} t + \varphi_S - \varphi_{LO}])\right) \quad [1.42]$$

The detected current components from a balanced detection setup, equation [1.42] are more by a factor of two when compared to single photodiode detection in equation [1.41] and is more by a factor of four compared to the direct detection scheme, equation [1.40]. The increase in the generated photocurrent in a coherent detection scheme comes with the improved receiver sensitivity, increased unamplified transmission reach and more tolerance to transmission impairments [57, 74, 75]. The availability of the in phase and quadrature signals allows demodulation of higher order modulation formats by driving information from both the amplitude and phase of a complex signal.

In summary, this chapter has given an insight into the transmitter and receiver section of an optical communication link and their respective technologically advances. The chapter opened with an explanation on the performance parameters of a high speed optical communication link, which included channel capacity, spectral efficiency and receiver sensitivity. The main modulation technologies, direct modulation and external modulation with emphasis on electro-absorption and Mach-Zehnder modulators were discussed. The different digital modulation formats, amplitude shift keying, phase shift keying and frequency shift keying and how they are integrated to come up with higher order modulation formats was also a subject of discussion in this chapter. The chapter concludes with a detailed discussion on the different detection technologies to properly demodulate data from the several modulation formats. The two main detection schemes discussed are direct detection and coherent detection. The next chapter will highlight on the transmission impairments and the digital signal processing procedures used to monitor and evaluate the performance of the entire optical communication link.

# Chapter 3

# 3 Signal transmission in an optical fibre and digital signal processing

## 3.1 Introduction

This chapter gives an account of the different fibre transmission impairments and the relevant digital signal processing (DSP) techniques for signal recovery and link performance stability evaluation. Linear fibre impairments, chromatic dispersion (CD) and polarization mode dispersion (PMD) are explained with emphasis on how they negatively impact on the bit error ratio (BER) performance of an optical communication link. Inter-channel self-phase modulation, together with intra-channel effects of cross phase modulation and four-wave-mixing are the nonlinear effects discussed in this chapter. The chapter ends with a discussion of digital signal processing (DSP) techniques used as a tool for signal recovery and overall optical link performance evaluation through bit error ratio (BER) computations. The bit for bit and quality (Q) factor DSP techniques and their capabilities to evaluate signals from different modulation formats conclude the chapter.

## 3.2 Benefits of an optical fibre as a transmission medium

Optical fibres which were intensely studied and implemented starting in the 1970s are the transmission medium of choice in a high speed optical communication link. Data transmission in an optical fibre that allows bundling together all the communication service requirements, such as telephone, video, television and mobile data at high speed in both enterprise and service provider networks comes with advantages of [76]:

- Great transmission capacity i.e. high bandwidth
- Low loss in the order of 0.2 dB/km
- Low signal distortion and dispersion
- Signal immunity to electromagnetic interference
- High signal security

Depending on the type of application and the reach to be achieved, optical fibres have been divided into two categories, namely single mode fibre (SMF) and multimode fibre (MMF). SMF allow one mode of propagation whereas the MMF supports several modes.

The major differences between the two categories are the variations in the transmission range, the number of different wavelengths or channels at which the light is transmitted and lastly the speeds at which those signals can travel [66, 77]. In optical communication, most SMFs operate in the 1310 nm and 1550 nm windows with minimum attenuation and are used for long reach transmission. On the other hand MMF which are designed for short range reach operate in the 850 nm and a few at 1310 nm transmission window [66].

### 3.3 Basic signal propagation equation

An optical fibre is a waveguide (optical wire) used for transmission of an optical signal that carries the information. The goal of a communication system is to propagate a signal from the transmitter to the receiver with minimum distortion, so that the signal at the receiver will be identical to the transmitted signal. Figure 3.1 below shows the geometry of the optical fibre and how the optical signal propagates along the z axis of the core of the fibre.

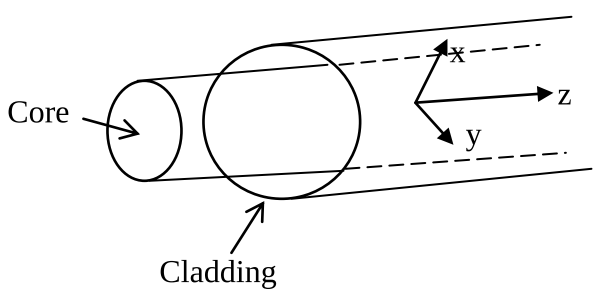


Figure 3.1: Geometry of an optical fibre

The complex notation of the electric field E(r,t) of the optical signal propagating inside a single mode fibre is given by:

$$E(r,t) = Re[\hat{e}F(x,y)A(z,t)\exp(i\beta_0 z - i\omega_0 t)] \qquad [3.1]$$

The term $F(x,y)$ represents the spatial profile of the fibre mode and $\hat{e}$ is the polarization unit vector. The pulse amplitude $A(z,t)$, which is independent of x and y leaves us with the task of solving a simple one dimension equation showing the variation of the pulse amplitude along the z axis as a function of time [1].

### 3.3.1 General pulse propagation equation

The quality of the signal degrades as it propagates along the fibre due to transmission impairments along the link. The general pulse envelope as the signal propagates along the fibre is expressed as:

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} = i\gamma|A^2|A - \frac{\alpha}{2}A \qquad [3.2]$$

A is the electric field, α is the attenuation coefficient, β are the dispersion parameters, γ is the nonlinear coefficient, z and t are the propagation direction and time, respectively [23, 78]. The $\beta_1$ term corresponds to the constant delay that the pulse experiences along the fibre during propagation, but has no effect on the quality of the overall signal and therefore can be neglected.

### 3.3.2 Non-linear Schrodinger equation (NLSE)

The third order $\beta_3$ dispersive effects are practically negligible and are not considered. Hence setting the first and third order dispersive terms to zero in equation 3.2 gives:

$$\frac{\partial A}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\gamma|A^2|A - \frac{\alpha}{2}A \qquad [3.3]$$

The solution to the nonlinear Schrodinger equation [3.2] whose behavior is governed by the existence of the nonlinear parameter $\gamma$ is obtained after setting the attenuation parameter α = 0. Each of the two terms (α and $\gamma$) mentioned in equation 3.2 describe both the linear and nonlinear impairments that cause signal distortion and need to be compensated for if error free transmission is to be achieved [23].

## 3.4 Transmission impairments

An optical fibre is often mistaken for a perfect transmission medium with almost limitless bandwidth, but in practice the propagation through an optical fibre is beset with several limitations especially as distance is increased to multi-span amplified systems. As the transmission systems evolved to longer distances and higher bit rates, the linear effects, which are attenuation and dispersion become important limiting factors [76]. The degree to which fibre impairments are compensated for determines the transmission capacity of an optical fibre transmission systems [79].

### 3.4.1 Attenuation

Attenuation causes the decay of signal strength or loss of light power as the signal propagates along the fibre. Attenuation in optical fibres is caused by both intrinsic and extrinsic factors. Intrinsic factors include scattering and material absorption, whereas extrinsic factors which are waveguide related include stress from the manufacturing process, environmental and physical bending.

Considering only the effects of attenuation α and neglecting the effects of chromatic dispersion (CD) and Kerr nonlinearity γ, equation [3.2] can be solved to give:

$$|A(t,z)|^2 = |A(t,0)|^2 e^{-\alpha z} \qquad [3.4]$$

Where α is the attenuation coefficient with units of dB/m.

It is important to note from equation 3.4 that the attenuation increases exponentially with increasing transmission distance.

The attenuation coefficient (also known as fibre losses) is expressed in dB/km using the relation:-

$$\alpha\left(\frac{dB}{km}\right) = -\frac{10}{L}\log_{10}\frac{P_T}{P_0} \qquad [3.5]$$

where α is the attenuation coefficient, $P_T$ and $P_0$ are the transmitted optical power and launch optical power respectively.

Multiple contributions to an overall transmission value arise from intrinsic fibre material properties as well as attenuation mechanisms associated with fibre fabrication. The different processes add to the observed reduction in transmitted power $P_T$ through contributions to the magnitude decrease and wavelength dependence of the total attenuation coefficient $\alpha_{total}$.

Optical absorption involves the direct transfer of energy from the propagating light beam to the material structure, resulting in the excitation of the material to a higher energy state. The phase velocity $v_g$ of radiation at a specific frequency in a specific material is related to the refractive index of the material by the following expression [23].

$$n_g = \frac{c}{v_g} \qquad [3.6]$$

where $n_g$ is the group refractive index and c is the speed of light

The group velocity refractive index can be written in terms of the wavelength dependence of the refractive index as:-

$$n_g = n - \lambda\frac{dn}{d\lambda} \qquad [3.7]$$

The attenuation coefficient therefore is expressed as:-

$$\propto(\omega) = \frac{2\omega k}{c} = \frac{2\omega k}{v_g(n-\lambda\frac{dn}{d\lambda})} \qquad [3.8]$$

where α(ω) = absorption coefficient

Equation 3.8 gives the relationship between the absorption coefficient and the group refractive index of the material. Evaluation of equation 3.4 indicates that the absorption coefficient contributes directly to the output power observed through its participation in the overall attenuation coefficient, $\alpha_{total}$. The material composition and specific structural characteristics directly impact the optical absorption observed at a particular wavelength of light.

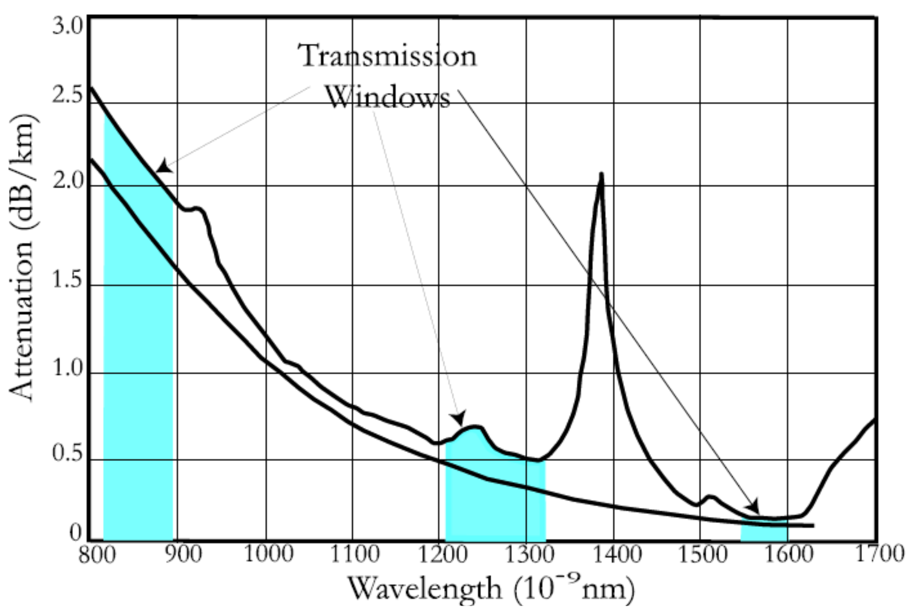


Figure 3.2: Absorption in optical fibre [69]

Figure 3.2 illustrates the variation of attenuation with wavelength taken over an ensemble of optical fibre cable material type (silica in this instance). Three principal windows of operation are shown in figure 3.2 labeled in a light blue colour. Depending on the optical frequency range, a window corresponds to a certain attenuation region and matches the ability of a transmitter to generate light efficiently and the receiver to detect it correctly.

- The first window which was used in the late 1980's with frequency centered at 850 nm with typical values of attenuation of 2 to 3 dB/km[23].
- Second window ('0' band) centered around 1300 nm with typical values of attenuation of 0.4 to 0.5 dB/km.
- Third window that corresponds to the "C" and "L" band is centered around 1550 nm with attenuation of 0.2 to 0.25 dB/km [26, 77].

### 3.4.2 Chromatic dispersion (CD)

Chromatic dispersion (CD) is the time domain broadening of the signal pulse width due to dependence of the refractive index of the material of the fibre on the wavelength of the optical carrier signal. On transmitting digitized pulses, they are converted into broadened Gaussian pulses. Chromatic dispersion (CD) effect is due to the non-existence of an optical source with a single wavelength output, rather they emit a narrow range of wavelength (a band of spectral width). Dispersion leads to distortion or degradation of the signal quality at the output due to overlapping of the pulses (inter-symbol interference), causing an increased bit error ratio [66, 80]. Figure 3.3 shows the phenomena of chromatic dispersion which will lead to introduction of errors in an optical transmission link due to pulse broadening.

Figure 3.3: Dispersion effect in an optical fibre [71]

Removing the effects of attenuation and nonlinear effects, equation [3.2] transforms to a linear system that corresponds to an optical transmission link of low power.

$$\frac{\partial A}{\partial z} = i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} \quad [3.9]$$

where $\beta_2$ is the group - velocity dispersion (GVD) parameter often called dispersion.

Group-velocity is the traveling speed of a light pulse in the fibre and it is a function of frequency $\omega$, therefore different spectral components of the signal travel at different group velocities leading to the CD.

An analytical solution of equation 3.5 is much simpler in the frequency domain using the Fourier transforms and is given by:

$$A(z,\omega) = A(0,\omega)e^{j\frac{\beta_2}{2}\omega^2 z} \quad [3.10]$$

The above solution shows that in the frequency domain the chromatic dispersion brings a distortion on the phase of the signal spectrum without changing the total spectral power distribution and at the end of the propagation the resultant pulse is broadened. The group velocity dispersion (GVD) parameter $\beta_2$ gives the time delay between two different spectral component separated by a certain frequency interval and it has units $s^2m^{-1}$. Usually the dispersion is measured with the dispersion coefficient D defined as:

$$D = -\frac{2\pi C}{\lambda^2}\beta_2 \quad [3.11]$$

D gives the time delay between two different spectral components separated by a certain wavelength interval and it has units ps/nm.km. Dispersion length, which is the propagation distance after a Gaussian pulse is broadened by 40 %, is given by:

$$L_p = \frac{\tau_p^2}{|\beta_2|} \quad [3.12]$$

where $\tau_p$ is the pulse half width [78].

### 3.4.3 Chromatic dispersion compensation

Dispersion compensation is one of the most important features required in optical fibre communication systems because its absence will lead to pulse spreading, that causes the output pulses to overlap thereby increasing the bit error ratio [66, 81]. Different chromatic dispersion compensation techniques have been implemented in optical networks. Chromatic dispersion can be compensated at three different points within an optical communication system, at the transmitter, within the transmission medium or at the receiver. Various dispersion compensation techniques to include the use of dispersion compensating fibres (DCF), electronic dispersion compensation (EDC), fiber Bragg grating (FBG) and digital filters were studied and implemented [81].

DCF is an in-line CD compensation technique, in which a loop of fibre having negative dispersion equal to the dispersion of the transmitting fibre is inserted at either the beginning (pre-compensation techniques)or end (post-compensation techniques) of an optical communication link. Pre-compensation is preferred as it is robust to non-linear phase noise [82]. Another technique that can be implemented, is dispersion managed (DM) cables also known as reverse dispersion fibre (RDF) that is based on mixing in each individual span a positive dispersion fibre and a negative dispersion fibre that cancels the overall dispersion and has the advantage of reducing the effects like, four wave mixing (FWM) and cross phase modulation (XPM).

Electronic dispersion compensation (EDC) is a post-compensation technique that involves electronic correction and equalization of the signal at the receiver. More recent and advanced techniques make use of forward error correction to recover the correct signal at the receiver [66]. In the digital domain, digital signal processing techniques can also be used to compensate for chromatic dispersion in optical communication networks.

Fibre Bragg grating (FBG) is an all-optical passive device that is used for chromatic dispersion compensation by recompression of the dispersed optical signal. In this technique, chirped fibre grating (CFG) is preferred. CFG is a small all-fibre passive device with low insertion loss that is compatible with the transmission system and CFG's dispersion can be easily adjusted [81, 83]. CFG should be located in-line for optimum results but come with complexity on its design.

Digital filters using Digital Signal Processing (DSP) can be used to compensate for chromatic dispersion. They are important for they provide fixed as well as tunable dispersion compensation for wavelength division multiplexed systems [81, 83].

### 3.4.4 Polarization mode dispersion (PMD)

In long haul transmission link, standard single mode fibres (SSMF) are used. As the signal propagates along the fibre it experiences polarization mode dispersion (PMD) in addition to the chromatic dispersion. Polarization is a wave phenomenon of light as it travels in a medium with its two components, the fast axis and slow axis, at right angles to each other. An optical fibre has a different index of refraction for each of those components of the light wave, which is called birefringence.

The propagating electric field in the fibre is described as a single mode comprising of two degenerate modes and each of the modes correspond to an orthogonal polarization state. The degeneration is due to the cylindrical symmetry of the optical fibre. A practical optical fibre however is not perfectly cylindrical due to some mechanical stress, tension and temperature fluctuations along the link. The presence of the imperfections exposes the two modes to varying refractive indices making the fibre to exhibit birefringence property. The birefringence makes the two modes to travel at different group velocities thereby arriving at the receiver at slightly different times leading to errors in the detected signal. Figure 3.4 shows how the signal gets distorted due to PMD [16, 84].

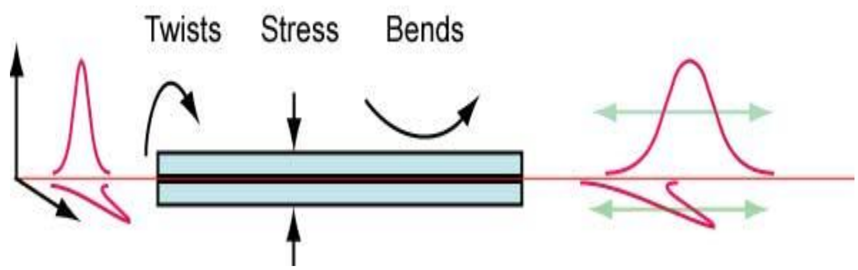


Figure 3.4: Illustration of PMD in an optical fibre [71]

The magnitude of PMD in a fibre is expressed as the difference in arrival times, which is known as the differential group delay (DGD) expressed as $\Delta\tau$. The state of polarization varies during the propagation, and hence PMD is stochastic in nature as a result of the randomness of its origin. In an optical fibres, mode coupling enables transfer of energy from one ideal mode to another during propagation. Mode coupling can be induced by random or intentional external perturbations, bends and stresses leading to the statistical nature of PMD.

The total DGD is given by:

$$\Delta\tau = D_g\sqrt{z} \qquad [3.13]$$

Where Dg is the PMD coefficient and its typical value is in the range between0.1 and 1 ps/km.

### 3.4.5 Polarization stabilization in optical fibres

Polarization mode dispersion (PMD) is an important linear phenomenon occurring inside an optical fibre, which can cause the optical receiver to incorrectly interpret the received signal resulting in high bit error ratios. Polarization state of an optical signal as it propagates along a fibre varies over time in an unpredictable manner [85]. Some active polarization stabilization techniques are required to keep an accurate correlation between the state of polarization of the light at the input and output of the fibre. Dynamic polarization control, using a fibre squeezer or arranged wave plates with fixed orientation and variable retarders were used to control polarization fluctuations [66]. In the recent past polarization stabilization was achieved by using special types of fibre known as polarization maintaining fibres (PMF). PMFs are designed to maintain a particular state of polarization throughout the fibre portion. In the digital domain, digital signal processing algorithms were developed to compensate for the effects of PMD in an optical communication network [75, 86-88].

### 3.4.6 Nonlinear effects (NL)

The nonlinear effects in an optical fibre is a result of either the intensity dependence of the refractive index of the medium or due to inelastic scattering phenomenon [89]. The origin of the nonlinear response comes from the interaction of the electromagnetic field with silica electrons that make up the fibre [78]. There are two nonlinear scattering phenomenon in fibres and both are related to vibrational excitation modes of silica. These phenomenon are known as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The fundamental difference is that, the optical phonons participate in SRS while SBS is through acoustic phonons. As a result of this difference, SBS occurs only in one direction i.e. backward while SRS can occur in both directions-forward and backward [89].

A solution to the NLSE in the absence of the chromatic dispersion coefficient is given by:

$$A(t,z) = A(t,0)e^{j\emptyset NL(t,z)} \quad [3.14]$$

where $P_0$ has information about the pulse peak and $\emptyset NL(t,z)$ is the nonlinear phase shift given by:

$$\emptyset NL(t,z) = \gamma P_0 |A(t,0)|^2 . \frac{1-e^{\alpha z}}{\alpha} \quad [3.15]$$

The power dependence of the refractive index is responsible for the Kerr-effect. Depending upon the type of input signal, the Kerr-nonlinearity manifests itself in two main categories namely intra-channel and inter-channel nonlinear effects. The intra channel deals with the nonlinear effects of a single channel on itself, a phenomenon called self-phase modulation (SPM). SPM brings a widening of the spectrum while the shape of the pulse remain unchanged, resulting in the interference of the signals within the same channel. On the other hand inter-channel nonlinearity deals with the effects due to neighboring channels. These manifests mainly in a wavelength division multiplexing system were several signals are transmitted at different wavelengths and neighboring channels interfere with each other, yielding cross-phase modulation (XPM). The presence of different wavelengths within the same fibre will also result in the signal interfering, generating new frequencies, a phenomena called four wave mixing (FWM) [23, 78, 87,89].

### 3.5 Power budget in an optical communication link

In an optical communication link, there are gains and losses encountered as light pulses propagate along the entire link. A system power budget is the most important task in the design of an optical fibre link to determine the maximum range of the transmission path. This helps to find the optimal parameters of transmitting and receiving devices to ensure proper signal transmission [26, 66, 90].

The power budget is the difference between the output power of the transmitter and the input power requirements of the receiver. The receiver has an operating range determined by receiver sensitivity at an acceptable BER threshold of $10^{-9}$. The available power to budget on is given by:

$$P_B = |R_S - P_0| = -P_{gain} + C_L + M_S \qquad [3.16]$$

where $P_B$ is the available power to budget (dBm), $R_S$ is the receiver sensitivity (dBm), and $P_0$ is transmitter output power (dBm), $C_L$ are the channel losses to include fibre and connection losses (dBm). $P_{gain}$ is the channel gain mainly from amplifiers and $M_S$ is the system margin, which is power loss due to components aging and degradation.

### 3.6 Digital signal processing (DSP)

The transition to higher data rates in a long-haul optical communications systems, witnessed in the last few years, is due to the gradual adoption of spectrally efficient multilevel modulation formats in conjunction with digital signal processing (DSP) algorithms at the receiver [57, 91]. When a light signal propagating in an optical fibre channel arrives at the receiver, the optical to electrical signal conversion can significantly slow down the overall transmission speed within the link. The recent advances in electronic processing capability have made possible the extensive signal processing at the highest commercial data rates. By using electronic digital signal processing we can replace expensive optics with inexpensive electronic processing circuits[92]. Digital signal processing is a group of techniques and algorithms that are optimized to deal with high speed numerical operations or analysis of signals, in either discrete or continuous time, to perform useful operations on those signals. In most cases, these signals originate as sensory data from the real world physical phenomena such as sound waves, seismic vibrations or visual images [91, 93].

Optical communication systems are currently undergoing a real technological revolution through the use of digital signal processing (DSP) techniques for improving the accuracy and reliability of the optical the links [55, 91, 94, 95]. Digital signal processing (DSP) algorithms have been studied to compensate for physical layer impairments in optical fibre communication systems. The physical layer impairments investigated include optical fibre chromatic dispersion (CD), polarization mode dispersion (PMD) and the nonlinear effects. At the receiver end the DSP technique was also studied for tracking light sources frequency shifts, phase offset and phase noise [17, 78, 87, 96].

Recent advances in DSP techniques were the major drivers in the rebirth of high spectral efficient transmission capacity with coherent detection, in optical communication networks. The major previous obstacles to manage the phase and state of polarization of the optical signal are now realized in the electrical domain using DSP techniques. Moreover, coherent detection in conjunction with DSP techniques have made it possible to compensate for optical fibre transmission impairments, opening up new possibilities that will likely shape the future of optical transmission technology [84].

## 3.7 Digital signal processing based coherent receiver

### 3.7.1 Digital carrier phase estimation

In a coherent detection scheme shown in figure 2.13, the coherently detected signal is given by:

$$E(t) = A \exp [j(\theta_s(t) + \theta_c(t))] \quad [3.17]$$

where the optical carrier phase $\theta_c(t)$is the phase of the transmitter laser referenced to the local oscillator (LO) and $\theta_s(t)$is the data phase and takes one of the four values: $\theta_s(t) = 0, \pm\frac{\pi}{2}, \pi$ .

Phase locking in the hardware domain can be replaced by phase estimation in the software domain using DSP technique. Figure 3.5 shows a schematic diagram of the algorithm for DSP based phase estimation.

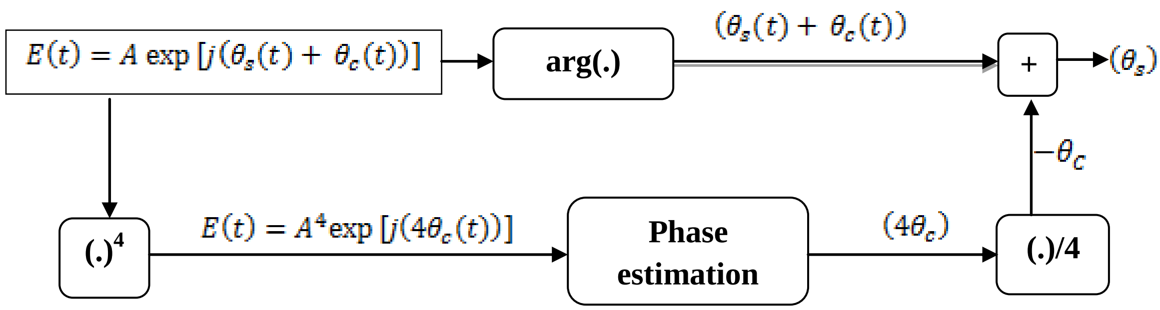


Figure 3.5: Phase estimation algorithm

The complex received signal is digitized by using an analog-to-digital converter (ADC) and processed in the software domain by using DSP techniques[84]. The received signal is raised to the fourth power to eliminate the data phase and to give the phase drift between the local oscillator and the transmitter laser.

$$A^4 \exp[j(4\theta_s(t) + 4\theta_c(t))] = A \exp[j(\theta_c(t))] \quad [3.18]$$

It is noted that, $\exp[j(4\theta_s(t))] = 1$ for all the possible values of $\theta_s$and as a result the power operation strips off the data phase. The carrier phase can then be computed and subtracted from the phase of the received signal to recover the data phase and the actual transmitted bits as shown in figure 3.5.

In our work DSP techniques were used mainly at the receiver end of the optical communication link for signal filtering to remove power line noise, for signal sampling and reconstruction and finally for the overall link performance monitoring through bit error ratio (BER) measurements. These developed techniques are very useful because of their stability in error detection, correction and their reduced vulnerability to noise and to system aging effects.

### 3.7.2 DSP algorithms for optical communication system performance evaluation

At the receiver end of an optical communication link, the pass band optical signal is down converted to the baseband original electrical signal. During transmission the signal quality is degraded due to linear and nonlinear impairments in the fibre and noise added at the receiver.

DSP techniques are implemented to reconstruct and accurately estimate the system bit error ratio (BER) by collecting the statistical distribution of the received analogue data samples [97]. The bit error ratio (BER) performance of an optical communication system is a figure of merit that allows different designs to be compared in a fair and consistent manner.

In the following sections, two DSP techniques to evaluate the optical communication link performance are discussed. The studied evaluation methods are bit for bit and the quality (Q) factor technique. The DSP techniques were developed and implemented in MATLAB (Matrix laboratory) a fourth generation programming language, to evaluate the optical link performance.

### 3.7.3 Bit for bit BER calculation

Ideally, the desired and ultimate goal in optical communication systems is to transmit a signal overlong lengths of fibre, at high bit rates and receive it error free. In practice the upper limits of transmission length and bit rate are a result of the possibility of an unacceptable number of errors in the received signal [98, 99]. When designing an optical communications system, BER is a key objective of the system design and is a measure of success. BER is affected by the link speed, its power, the distance and the amount of noise among other factors.

BER is defined as the ratio of the bits received in error to the total transmitted bits in an optical transmission system. This can be directly translated into the number of errors that occur in a string of a stated number of bits [98, 100].

$$\text{BER} = \frac{\text{Bit received in error}}{\text{Total number of send bits}} \qquad [3.19]$$

The above relationship suggests that the rate at which transmitted '1' and '0' bits are received in error is calculated by simply comparing the transmitted sequence to the received sequence on a bit for bit bases. However BER measurement is not a trivial process. It requires sophisticated and expensive equipment or complex DSP algorithms to achieve accuracy, particularly at high bit rates.

The bit for bit BER measurements techniques gives the most accurate results at a cost of longer computational times and larger data storage space. In a 10 Gbps data sequence, there are $10^{10}$ bits of data within one second and large memory size is required to process these data through DSP. Such huge storage space is a constraint in the sampling oscilloscopes that we experimentally use as analogue to digital converters (ADC).

### 3.7.4 The Q factor technique for BER measurements

The rapid growth in demand for communication has necessitated an upgrade in the transmission capacity of an optical communication system. This should be coupled with a more time efficient but reliable method to estimate the BER of the system [30, 33, 98]. A statistical method, which uses the analogue parameters of the signal to compute the fidelity of the recovered baseband signal, is a suitable alternative. The Q-factor is a parameter that directly reflects the quality of a digital optical communication signal. The higher the Q-factor, the better the quality of the optical signal [101, 102]. The Q-factor is the optical signal-to-noise ratio (OSNR) of the analogue signal and it gives a measure of the propagation impairments caused by optical noise, non-linear effects, polarization effects and chromatic dispersion [62, 103-105].

#### 3.7.4.1 The Q factor technique for a two level system

The decision circuit in a fibre optical communication receiver, demodulates the signal by comparing the sampled voltage, V(t), to a reference value, $V_{TH}$ called the optimum decision threshold. An assumption is made that the additive white Gaussian noise (AWGN) is the dominant cause of erroneous decisions, and then the statistical probability of making such a decision can be calculated. To determine the probability of error we need to know the signal probability distribution functions (PDF) for the 'zero' and 'one' levels i.e. the probability that the sampled signal level will fall below or above the decision threshold.

According to figure 3.6 the badly received bit is the overlapping region between PDF of zero symbol and one symbol.

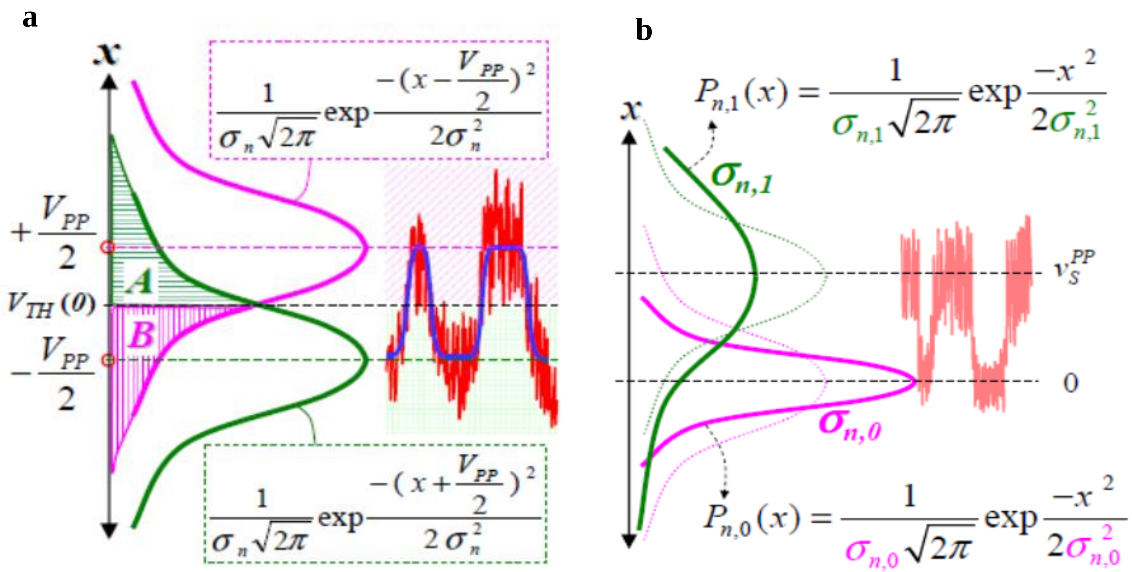


Figure 3.6: Probability density function for (a) balanced two level (b) unbalanced two level systems [101].

The total probability that a '0' bit is recorded in error as a '1' bit, $(P_{01})$ is the area under the probability distribution function (area A) and is given by:

$$P_{01} = \frac{1}{2}\int_0^{\infty} \frac{1}{\sigma_{n0}\sqrt{2\pi}} \exp -\left[\frac{(x-\frac{V_{pp}}{2})^2}{2\sigma_{n0}^2}\right] \qquad [3.20]$$

Also the total probability that a '1'bit is recorded in error as '0' bit $(P_{10})$ is the area under the probability distribution function, (area B) given by:

$$P_{10} = \frac{1}{2}\int_{-\infty}^{0} \frac{1}{\sigma_{n1}\sqrt{2\pi}} \exp -\left[\frac{(x-\frac{V_{pp}}{2})^2}{2\sigma_{n1}^2}\right] \qquad [3.21]$$

where $\sigma_{n(0,1)}$ , x = V(t) and $\frac{V_{pp}}{2} = V_{TH}$ are the standard deviation for '0' and '1' level, the received signal voltage and the threshold value respectively for the balanced case where $\sigma_{n(0)} = \sigma_{n(1)}$ .

For the unbalanced case $(\sigma_{n(0)} \neq \sigma_{n(1)})$, as shown in figure 3.5 (b), the threshold value is not half way between the two symbols. This represents a more general and practical PDF for both the zero and one level and are expressed as:-

$$P_{(0,1)} = \frac{1}{2}\int_{V_{TH}}^{-\infty} \frac{1}{\sigma_L\sqrt{2\pi}} \exp - \left[\frac{(V_L - V_{TH})^2}{2\sigma_L^2}\right] \quad [3.22]$$

and

$$P_{(1,0)} = \frac{1}{2}\int_{V_{TH}}^{\infty} \frac{1}{\sigma_H\sqrt{2\pi}} \exp - \left[\frac{(V_H + V_{TH})^2}{2\sigma_H^2}\right] \quad [3.23]$$

The bit error ratio (BER) is determined by two factors:-

(i) The standard deviations of the noise for the zero (low) level ($\sigma_L$) and one (high) level ($\sigma_H$) and

(ii) The voltage difference between the zero level ($V_L$) and one level ($V_H$).

The above parameters relate to give the quality factor (Q- factor). The Q-factor defines the optical signal-to-noise ratio (OSNR) for a binary optical communication system and is expressed as:

$$Q_{(1,0)} = \frac{V_H - V_{TH}}{\sigma_H} = \frac{V_{TH} - V_L}{\sigma_L} \quad [3.24]$$

The above expression shows a way of representing the quality factor for both the zero and the 'one' level. The Q factor can also be written as:

$$Q = \frac{V_H - V_L}{\sigma_H + \sigma_L} \quad [3.25]$$

The analytical solutions to equations 3.22 and 3.23 are found by taking the normalized Gaussian function and introducing:

$$z = \frac{V_L - V_{TH}}{2\sigma_H} \quad [3.26]$$

Substituting equation 3.24 and 3.26 into equation 3.22 gives the well-known error function (erfc).

$$P_{(0,1)} = BER_{0,1} = \frac{1}{2}\int_{Q}^{-\infty} \frac{1}{\sqrt{2\pi}} \exp - \left[\frac{(z)^2}{2}\right] = \frac{1}{2} erfc\left(\frac{V_{TH} - V_L}{\sigma_L}\right) \quad [3.27]$$

The same procedures can be applied to equation [3.17] to give:

$$P_{(1,0)} = BER_{0,1} = \frac{1}{2}\int_{Q}^{-\infty} \frac{1}{\sqrt{2\pi}} \exp - \left[\frac{(z)^2}{2}\right] = \frac{1}{2} erfc\left(\frac{V_H - V_{TH}}{\sigma_H}\right) \quad [3.28]$$

Therefore the total BER for a two level system is given by:

$$BER = P_{(0,1)} + P_{(1,0)} = \frac{1}{2} erfc\left(\frac{V_{TH} - V_L}{\sigma_L}\right) + \frac{1}{2} erfc\left(\frac{V_H + V_{TH}}{\sigma_H}\right) \quad [3.29]$$

$$BER = erfc\left(\frac{V_H - V_L}{\sigma_H + \sigma_L}\right) \quad [3.30]$$

Equation 3.30 combines BER associated with the high and low levels into an overall system BER. This form of the Q factor simplifies both the measurement of BER and the calculation of the overall theoretical BER due to additive random noise [33, 102].

### *3.7.4.2* The Q factor technique for an M- array system

An M-array is a multilevel baseband signal with M signal levels or symbols. It is a more spectral efficient modulation format where each symbol will be carrying m bits given by:

$$m = \log_2 M \qquad [3.31]$$

In such a system there are M-1 threshold values. The above PDF procedures can be done at each threshold value on a multilevel system to determine the BER.

Consider a four level system with three threshold values. The total BER is calculated as follows:

$$BER = \sum_{n=1}^{M-1} \mathrm{erfc}\left(\frac{V_{Hn} - V_{Ln}}{\sigma_{Hn} + \sigma_{Ln}}\right) \qquad [3.32]$$

The same reasoning can be applied to any M -array level signal by setting the M-1 threshold values before calculation the BER [33, 62,106].

This chapter was dedicated to analyze the transmission impairments that arise as the optical signal propagates along the fibre. Both linear and nonlinear impairments were discussed. Detailed accounts were given on the effects of attenuation, chromatic dispersion (CD) and polarization mode dispersion (PMD). Different methods to mitigate the different impairments were also explained in detail. The last part of the chapter highlighted on digital signal processing (DSP) algorithms that were developed to recover both coherent and direct detected signals. The chapter ends with a discussion on the different performance evaluation techniques that were developed in the DSP domain namely the bit for bit and the quality factor technique. The next chapter is the first results chapter on both simulations and experimental work. The chapter will give a performance comparison between amplitude shift keying (ASK) and differential phase shift keying (DPSK) modulation formats.

# Chapter 4

# 4 Differential phase shift keying (DPSK) and Amplitude shift keying (ASK) modulation formats in a high speed optical communication system

## 4.1 Introduction

Fibre optical communication systems form the back bone of high capacity transport infrastructure that enables global ubiquitous broadband data services and advanced internet applications[30]. In modern optical communication systems, modulation format has a great impact on system performance and reliability [43, 107]. Among the different modulation formats implemented to date, they all share the same basic motive to improve the transmission fidelity, increase the data rate and increase the transmission distance between stations [38]. Most of the higher order modulation formats that have been intensively studied and implemented are derivatives from ASK modulation technique [6, 7, 33, 35, 68]. In recent studies a transmission speed of 50 Gbps has been achieved using a directly modulated vertical cavity surface emitting laser (VCSEL) [35]. In this chapter differential phase shift keying (DPSK) and amplitude shift keying (ASK) are discussed. The transmitter and receiver for each modulation format are discussed in detail in the proceeding sections. Digital signal processing (DSP) assisted receiver circuits were designed and implemented to evaluate the performance of the high speed optical communication system. The comparative performance of the two modulation modalities were demonstrated using virtual photonics instruments (VP1) simulation software. In a differential phase shift keying (DPSK) modulated signal, the optical power is the same for all transmitted bits and the separation between the transmitted symbols is large, making the technique more tolerant to the effects of dispersion in the link compared to ASK format [46, 68, 108]. An experimental demonstration to validate the reliability of the DSP aided receiver was performed using the ASK modulation format. Possible applications of the two modulation formats in different optical communication systems are highlighted.

## 4.2 Experimental and simulation design procedure

In the following sections of the research work, both experimental and simulation results for a 10 Gbps non-return-to-zero, amplitude shift keying (NRZ-ASK) scheme and differential phase shift keying (DPSK) modulation scheme are presented. The need to establish a performance comparison of the different modulation formats, virtual photonic instruments (VPI) simulation software was used. Phase modulators which are not available for experimental demonstration in the Centre for Broadband Communication (CBC) at NMMU, could only be investigated through a simulation.VPI software provides a powerful simulation environment for it has different modules emulating various components in a real experimental setting. These modules are briefly describes for the two modulation formats.

The transmitter module has a pattern generator, that will generates different pseudo-random bit sequences (PRBS) and a laser whose output is modulated by a NRZ electrical bit pattern generating '1' and '0' level states for the "On Off" keying modulation format. A universal fibre module with adjustable parameters such as attenuation, dispersion coefficient, effective area, nonlinear effects constants and length is used as the transmission medium. The other important modules are the optical attenuator, power meter and the signal analyzer that can be used to visualize the signal at different points along the link. The receiver module constitutes a photodetector (positive intrinsic negative (PIN)) or avalanche photodiode (APD) in addition to the bit error ratio (BER) estimation module.

Differential phase shift keying (DPSK) is a binary modulation format and is another alternative primary building block in the architecture of spectral efficient higher order modulation formats [68, 96, 109]. A DPSK transmission module comprises of an optical source(continuous wave, distributed feedback (DFB) laser source), a non-return to zero (NRZ) electrical binary data stream, precoder circuit and an externally modulated Mach-Zehnder modulator which encodes the electrical data onto the phase of the optical signal. A precoder is a requirement in the transmitter module to generate a new data sequence (differential coded data), using an XOR gate as explained in chapter two.

The DPSK receiver at the end of the link demodulates the transmitted data back to its original electrical form. An optical DPSK receiver decodes an optical differential phase shift keyed signal to an intensity keyed signal in an optical fibre communication network. The most important component in the receiver module is a Mach-Zehnder interferometer with a 1-bit period delay (T) in one arm and a pair of balanced photodiodes [16, 35,46]. It is at the output of the MZDI were the two signal interfere and the phase modulated signal is converted to intensity modulated signal prior to detection by the balanced photodiodes.

## 4.3 Digital signal processing aided receiver

### 4.3.1 Bit for bit BER measurement technique

A reconfigurable digital signal processing (DSP) circuit was developed to monitor and evaluate the performances of a two level digital optical communication system. The final goal of the DSP receiver is to monitor the bit error ratio (BER) performance of the entire optical communication system. BER is a figure of merit that allows different optical communication systems to be evaluated in a fair and consistent manner [110].

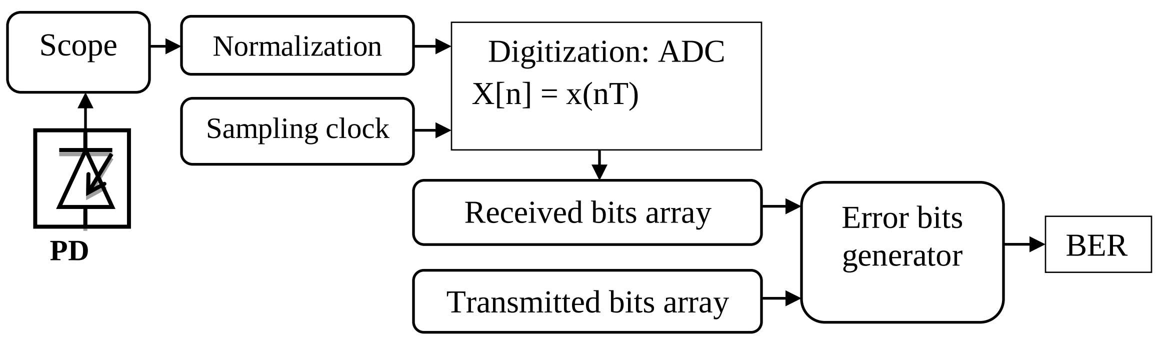


Figure 4.1: Block diagram for a digital signal processing (DSP) aided receiver

Figure 4.1 shows the functional block diagram for the developed DSP assisted receiver. It comprises of sub-circuits performing different but integrated functions. The role of the first DSP circuit is to normalize the received continuous time signals, which is represented by a sequence of numbers or samples stored in an array in the oscilloscope memory. The stored numbers or samples represent the amplitudes of the received analogue signal. The next circuit is an analogue to digital convertor (ADC). The ADC samples the continuous time analogue signal at bit period intervals and quantizes it into discrete amplitude magnitudes. Digitization of the analogue signal into an array of data bits was implemented using a D-type flip flop by comparing each sampled and quantized discrete amplitude value to a set threshold value [111]. Figure 4.2 shows a detailed logic circuit for the DSP aided receiver that was developed to evaluate the performance of a two level system. The functional operations of each circuit were developed in the software domain, using MATLAB.

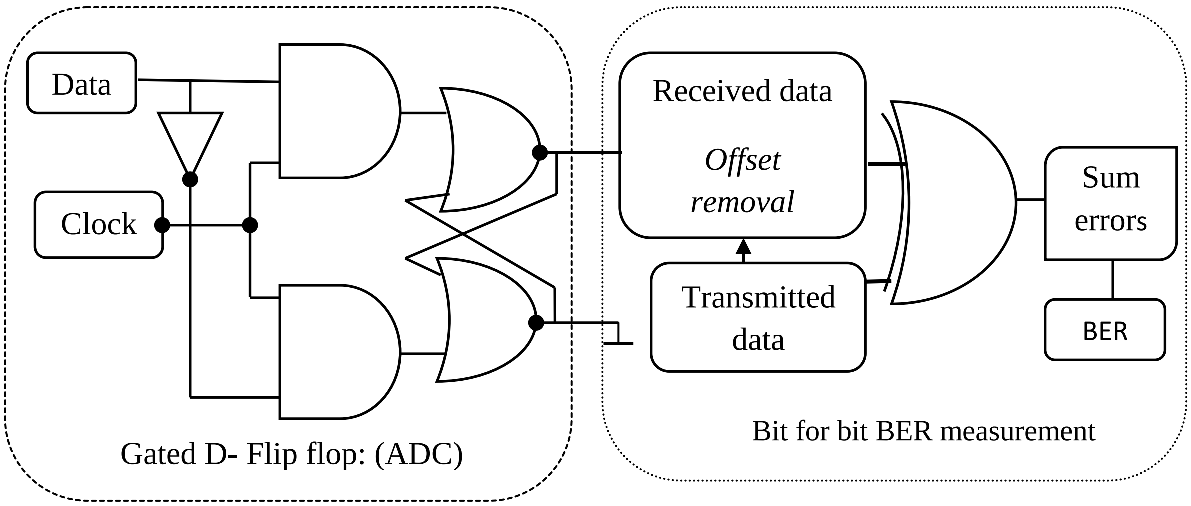


Figure 4.2: Logic circuit for the DSP receiver

The gated D-type flip flop is synchronized to the sampling clock signal and tracks the inputs, mapping the transitions to the output that matches those inputs values. At every clock sampling time, the input to the D-flip flop is compared to a set threshold value. A high '1' bit is output for an input value greater than the set threshold value whereas a low '0' bit is output for a value less than the threshold value.

The last DSP circuit has the most important function of computing the actual BER value. The BER is computed by comparing the transmitted and received data on a bit for bit basis in order to determine the total number of bits that were demodulated in error. The received sequence normally has more bits than the transmitted sequence since it is repeatedly sampled to accumulate the minimum billion bits required to meet the ITU standards on performance evaluation. However the starting point of the send pseudo random bit pattern is not known and as a result an offset has to be established between the transmitted and received bit sequence. The offset between received and transmitted bits has to be corrected before the actual BER calculation is carried out. A correlation of the two data arrays is done to determine the offset. The index value corresponding to the correlation peak is located to determine the offset. The erroneously demodulated bits are singled out by passing the received and transmitted data bits through an EXOR gate. The EXOR also known as an inequality gate, for it always outputs a high whenever the inputs are not the same. All the bits detected in error are summed up and the BER is computed using equation 3.13.

### 4.4 Simulation setup for DPSK and ASK modulation formats

Figure 4.3 shows the developed VPI simulation for both ASK and DPSK transmission setup used to generate and detect 10 Gbps signals. VPI is photonic simulation software supporting requirements for active and passive integrated photonics, fibre optic applications and optical transmission and networking systems. A 1550 nm DFB laser was used at the transmitter.

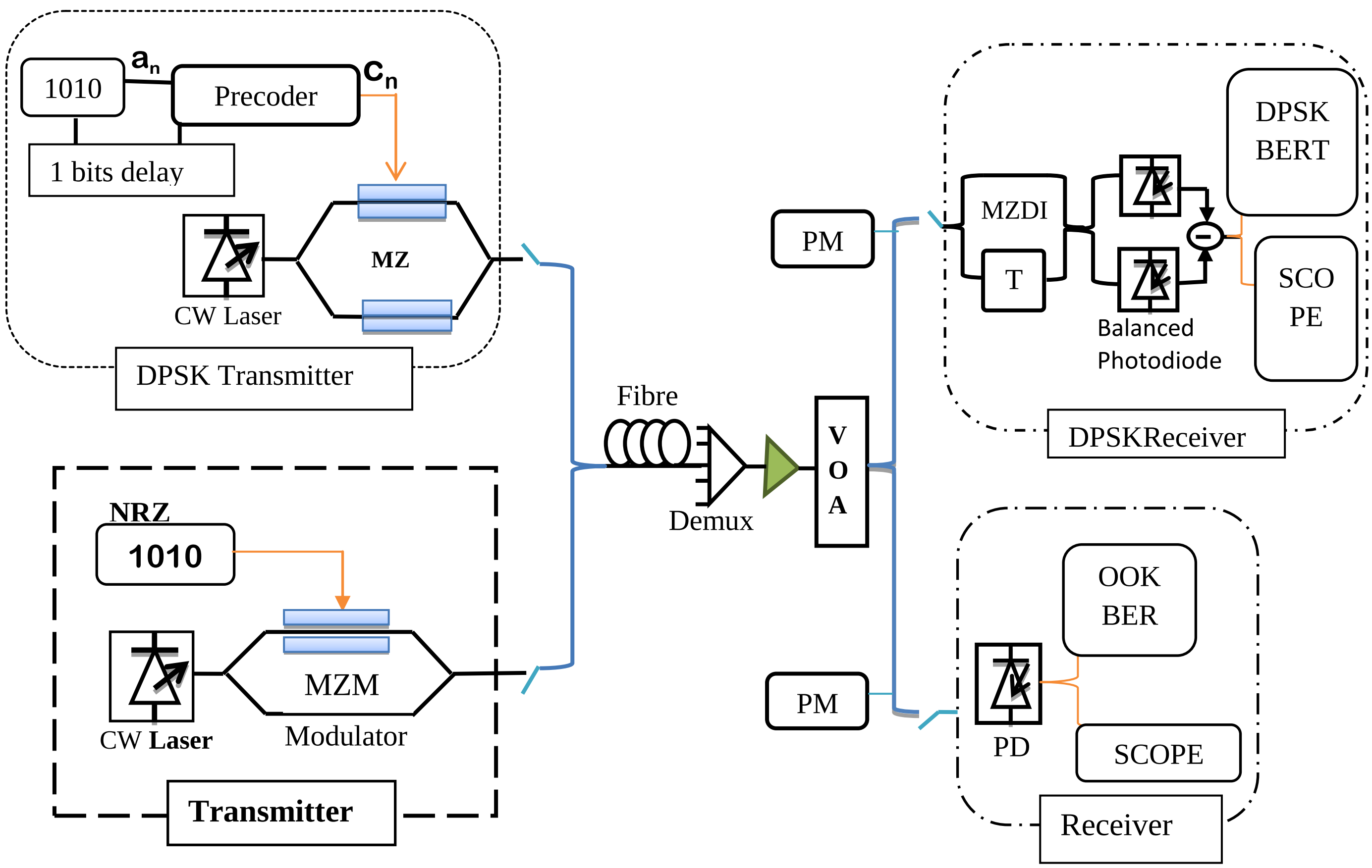


Figure 4.3: Simulation schematic diagram showing both ASK and DPSK modulation formats

For the case of a DPSK a MZM modulator was used to generate the DPSK signal. A pattern generator was used to generate a $2^7$-1 binary non return to zero (NRZ) pseudo random bit sequence (PRBS). The 10 Gbps NRZ data stream was pre-coded, to generate a new data sequence.

The new data sequence generated at the output of the pre-coder was used to modulate the 1550 nm laser signal in the MZM modulator. The modulated signal was launched into a G.652 fibre for transmission to the receiver. The de-multiplexer (DEMUX) in the link, acted as a narrow band pass optical filter to remove the broadband optical noise. After the DEMUX, the signal is amplified in the Erbium doped fibre amplifier (EDFA). A variable optical attenuator (VOA) emulates the actual link by varying the optical power getting to the receiver and the optical power getting to the receiver was measured by the power meter (PM). At the receiver a MZDI, was used to demodulate the signal. The received signal was split into two arms of the MZDI. In one arm, the received data sequence was delayed by one bit duration before the two signals were made to interfere at the output of the MZDI achieving phase to intensity conversion. Constructive and destructive signal intensities were detected by two balanced (PIN) photodiodes depending on the phase difference between two consecutive received bits. The output powers getting to the photodiode were governed by equation 1.20 and 1.21. A phase difference of zero means a one bit was transmitted and a phase difference of '$\pi$' means a zero bit was transmitted.

For ASK the 1550 nm laser signal was intensity modulated using an externally modulated MZM structure. The ASK signal was launched into the same transmission link that was used for DPSK setup before being directly detected by a PIN photodiode at the receiver.

The performance of an optical communication link should be monitored and evaluated for its fidelity and make sure it meets the set international telecommunication union (ITU) standards. The output of the PIN photodiode in the two setups was connected to a signal analyzer for signal monitoring and to a bit error ratio (BER) detector for measuring the BER and receiver sensitivity. BER measurements were achieved by programming the error detector with the transmitted information and compare it to the data sequence received at the output of the demodulator.

Using the VPI simulation setup shown in figure 4.3 and the above description, BER measurements were performed for different length of fibre using the two named transmission modalities.

### 4.5 Performance comparison between DPSK and ASK

#### 4.5.1 Dispersion penalties at different transmission distance

The optical communication system's tolerance and elasticity to the effects of dispersion were measured for different lengths of fibre. The measurements were performed using VPI simulation software. Simulation software are of paramount importance in science and engineering research for they provide insight into properties and features of systems which we might not have capacity to perform experimentally due to higher equipment cost. Additionally, simulations can be run before practical implementation as a safety measure to the equipment [66, 112].

The optical communication link performance was evaluated through BER measurements at different received optical powers. Different lengths of G.652 fibre were used in turns for the two transmission modalities. The G.652 fibre used has low attenuation but has very high chromatic dispersion parameter of 18 ps/nm.km at 1550 nm compared to 0.35 ps/nm.km at 1310 nm. The use of a G.652 fibre at 1550 nm yields non optimum performance due to the effects of chromatic dispersion and it therefore provides a better platform to compare the performance between the two modulation formats, ASK and DPSK respectively. Figure 4.4 shows the BER measurements for ASK for back-to-back transmission and for transmission on different fibre lengths.

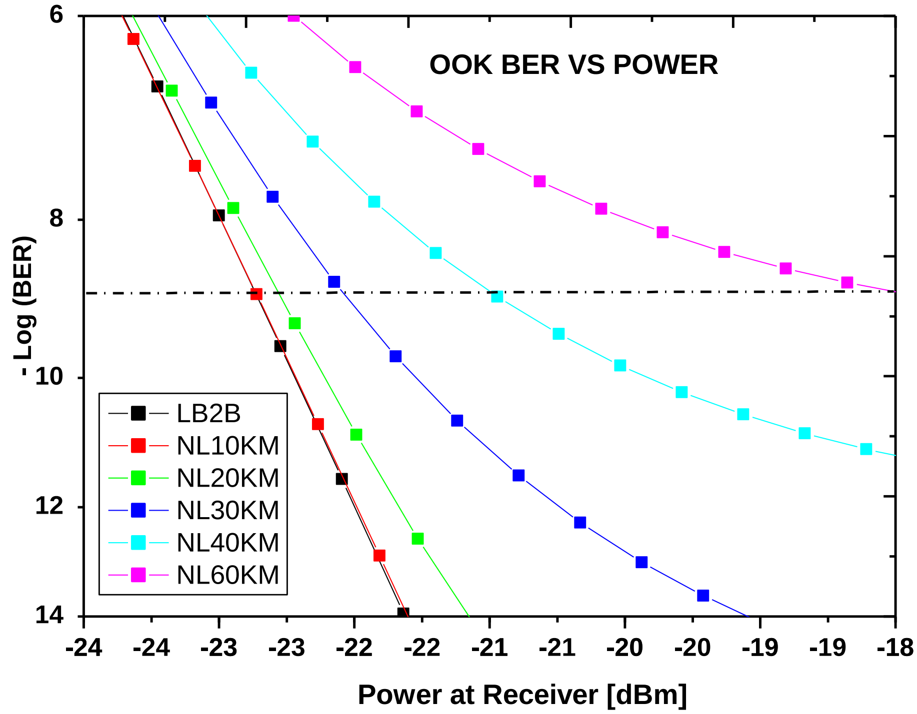


Figure 4.4: ASK BER measurements for back-to-back and for transmission over different lengths of G.652 fibre

From figure 4.4 a receiver sensitivity of -22.7 dBm was obtained. The value falls within the specified range of a PIN photodiode of (-18 to - 24) dBm. Experimental values for receiver sensitivity in the range of -19.3 dBm to -23.0 dBm were previously obtained using the same photodiode [66]. The receiver sensitivity gives the minimum optical power that the receiver requires to correctly demodulate the signal. At any power below the receiver sensitivity, the BER in the system will be high. BER value decreases at optical powers above the receiver sensitivity value, giving error free transmission.

On introducing a fibre into the link, additional optical power with be required for the receiver to decode properly. This additional power compared to the receiver sensitivity value, is known as the transmission penalty. Transmission penalties of 0.2 dB, 0.6 dB and 2.5 dB were obtained for transmission length of 20 km, 30 km and 40 km respectively. An error free transmission was achieved for a maximum distance of 40 km before getting an error floor at 60 km of G.652 fibre. The error floor which is graphically indicated by a sudden change in the BER curve shape as it fails to cross the minimum threshold BER of $10^{-9}$ as shown in figure 4.4. The error floor is independent of the received optical power, hence no-matter how much optical power is introduced into the system it will never cross the minimum threshold BER value. In this setup the error floor was mainly attributed to the high chromatic dispersion parameter of 18 ps/nm.Km for the G. 652 at of 1550 nm wavelength.

Optical communication link performance measurements were also performed for DPSK signal for back-to-back and for different lengths of the same G.652 fibre that was used in the ASK setup. Figure 4.5 shows the BER curves for back-to-back and for different length of fibre for a DPSK transmission setup.

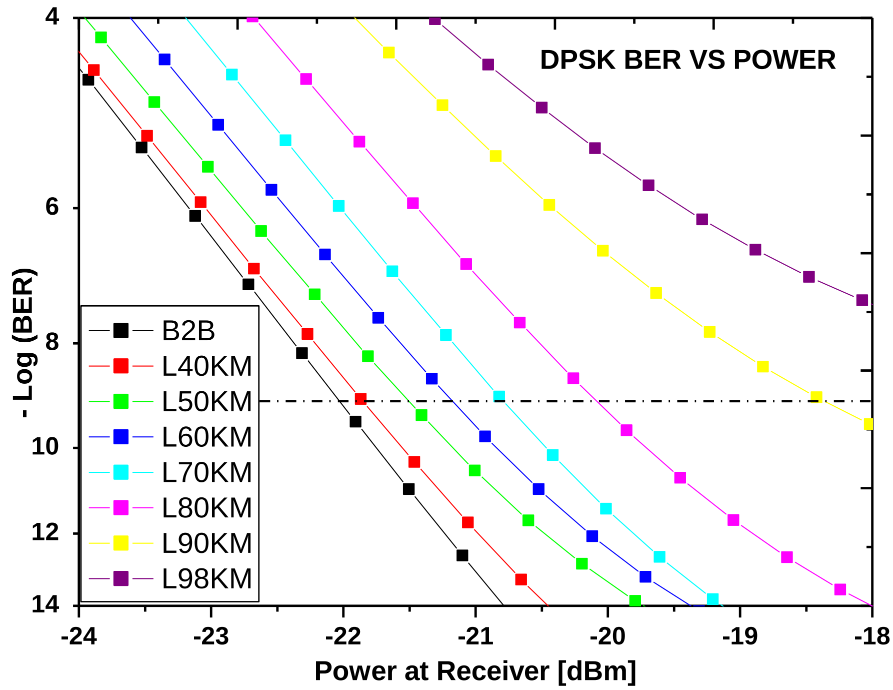


Figure 4.5: DPSK BER measurements for back-to-back and transmission over different length of G.652 fibre

From the simulation BER results plots in figure 4.5, a receiver sensitivity of - 22.0 dBm was recorded for the DPSK compared to - 22.7 dBm for the OOK setup, with the latter being 0.7 dB more sensitive. Transmission penalties of 0.1 dB, 1.0 dB, 2.0 dB and 3.7 dB were recorded for transmission length of 40 km, 60 km, 80 km and 90 km respectively. A maximum unamplified transmission distance of 90 km was achieved with acceptable errors and an error floor was obtained at 98 km of G.652 fibre. DPSK has achieved larger transmission distances compared to ASK, irrespective of the high chromatic dispersions (CD) in the G. 652 fibre at 1550 nm.

### 4.5.2 Transmission penalties for amplified and unamplified ASK and DPSK formats

On increasing the transmission distance the receiver requires extra power to demodulate the signal accurately [36, 66,113]. The extra power for each transmission length as compared to the receiver sensitivity for back-to-back at an acceptable optical communication BER of $10^{-9}$ is known as the transmission penalty**.** Figure 4.6 shows a graph of the transmission penalties for different transmission distances in the link.

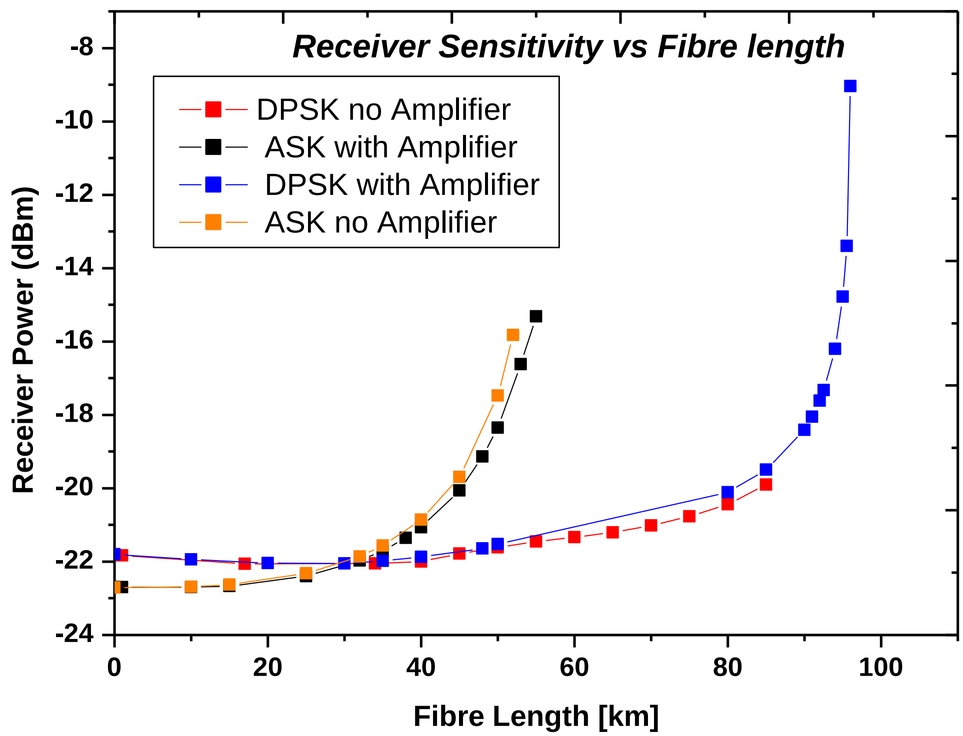


Figure 4.6: Transmission penalties on different transmission distances

In figure 4.6 the performance of the two modulation formats ASK and DPSK was analyzed and compared. From figure 4.4 and 4.5, it is evident that ASK gave a 0.7 dB better receiver sensitivity than the DPSK modulation format. It is further noted that for both the amplified and unamplified transmissions, ASK system performs better than DPSK system for distance less than 30 km. The fact that the effects of chromatic dispersion accumulates with increasing distance makes the legacy ASK modulation format a better candidate for short distance transmission. As can be seen from figure 4.6, for short distances the penalty values for ASK are significantly lower than for the DPSK modulation format.  However as the transmission distance increases, the effects of CD become pronounced, degrading the quality of the ASK signal, leading to high

BER. At distances greater than 30 km the performance of the DPSK system was superior to that of the ASK modulation format due to a factor of two increase in symbol points separation, which translates to 3 dB gain in received optical power as suggested in figure 2.9. As seen from figure 4.6, DPSK has an almost constant performance for distances of up to 50 km indicating its high tolerance to the effects of CD compared to ASK modulation format. An error floor for the amplified ASK scheme occurs at about 58 km compared to at about 98 km for the amplified DPSK formats. Basing on the above simulation results DPSK achieves an additional 40 km making it a better candidate for use in long haul transmission setups while the ASK system serves better in short range transmission systems.

## 4.6 Experimental demonstration of direct detection intensity modulation (IMDD) link with digital signal processing aided receiver

The experimental setup for direct detection intensity modulation is shown in figure 4.7. A 1550 nm WDM laser signal is intensity modulated at 10.3 Gbps in an external Mach-Zehnder modulator (MZM) with a non-return to zero (NRZ) electrical data stream and was transmitted through a single mode fibre. A polarization controller (PC) was used to launch the signal into the fibre. A variable optical attenuator (VOA) controls the power of the signal prior to detection and conversion to an electrical signal by the photodiode.

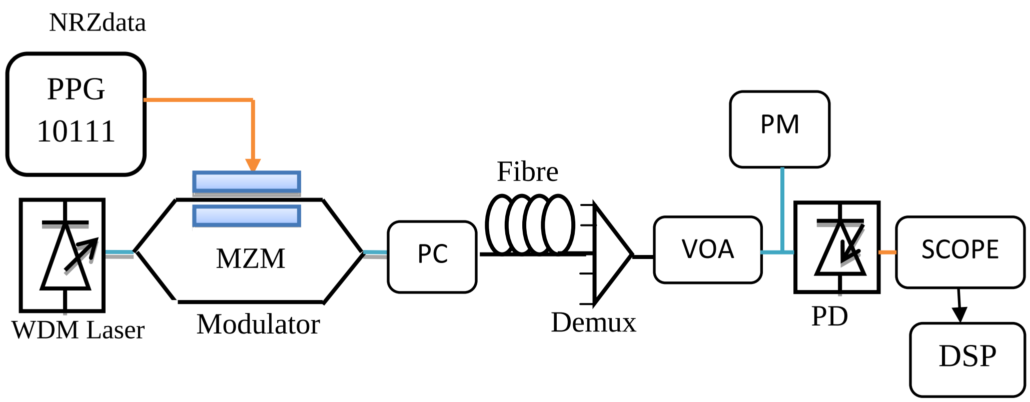


Figure 4.7: Experimental setup for intensity modulation direct detection (IMDD) scheme

An Agilent oscilloscope was used to acquire a measurement burst of the received transmitted analogue data, which is then transferred to a computer for offline processing. The received continuous time signal is represented with a sequence of numbers representing the amplitude of the signal at a specific instant in time. The received electrical signal is processed offline using relevant DSP circuits, to determine the BER as a measure of performance of the optical fibre transmission link.

### 4.7 Digital signal processing aided receiver validation

For intensity modulation, the receiver scheme comprises of a single photodiode, oscilloscope and the digital signal processing algorithm. A $2^7$-1 pseudo random binary sequence (PRBS) bit pattern sequence is transmitted at 10.3 Gbps at different attenuation values for back-to-back transmission. The developed DSP algorithm comprises of four integrated important sub-circuits. The function of the first part is to load the digital data saved in the sampling scope to an offline processing computer. The second part normalizes and digitizes the continuous signal into discrete bits using the gated D-flip flop shown in figure 4.2.

Figure 4.8 shows a plot of the analogue normalized received signal amplitudes plotted against time using a sequence of voltage values as sampled by the oscilloscope. The analogue signal was digitized using the ADC depicted in figure 4.2. The normalized analogue signal x (nT) is sampled at discrete times equivalent in integer multiples of the bit period (T), yielding an array of data bits X [n] expressed as X [n] = x (nT).

The ADC in figure 4.2 was implemented in the software domain to digitize the analogue sequence of samples x (nT) by comparing the average of the three middle points within a bit period to a set threshold value of the signal amplitude to obtain a binary array X[n]. If the average value is greater than the threshold value then the received bit is interpreted as a ‘1’ bit and when the average value is below the threshold value it is demodulated as a ‘0’ bit, as shown in figure 4.8.

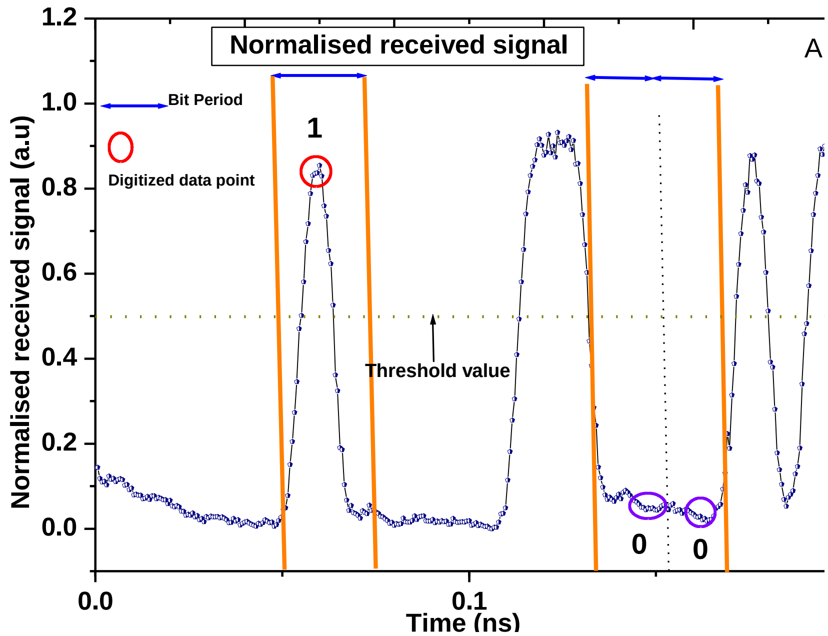


Figure 4.8: A DSP normalized and digitized signal as captured from the digital storage oscilloscope

The third part generates the pseudo random binary sequence (PRBS), ($2^7$-1) bit pattern, representing the send data bits and then compares it to the recovered data bits to determine the bit error ratio as illustrated in figure 4.1 and 4.2. The transmitted and received data streams are first correlated to establish the offset between them, before the BER calculation is done. The receiver sensitivity will be determined at an acceptable BER of $10^{-9}$, which means in a billion transmitted bits only one is allowed to be incorrectly detected.

The fourth and last part of the DSP algorithm plots the eye diagram. An eye diagram is a useful tool for qualitative analysis of the received signal in digital communication systems. It is a quicker way of visually assessing the signal quality. An eye diagram is generated by overlaying sweeps of different segments of a long data stream. Careful analysis of the eye diagram (visual display) allows the user to drive information such as of signal-to-noise, clock timing jitter and skew. Figure 4.9 (A to D) shows the DSP eye diagram plots at different optical power values. The plotted eye diagrams using the developed DSP circuits is similar to the one obtained using the hardware as shown on insert in figure 4.10.

Eye opening is a measure of quality of the received signal whereas eye closure suggests loss in the signal quality due to attenuation. Information is easily and reliably recovered from a wide open eye and very little or no information can be recovered from a closed eye diagram.

The performance of the DSP aided receiver was validated by comparing it with the performance of the commercial BER tester hardware. Figure 4.10 shows the BER curves for back-to-back measurement as evaluated using the commercial bit error ratio tester (BERT) and the developed DSP circuits. Receiver sensitivity values of -21.1 dBm and -19.8 dBm were obtained from the DSP aided receiver and from the commercial BERT tester respectively. The DSP aided receiver gave a 1.3 dB improvement in receiver sensitivity.

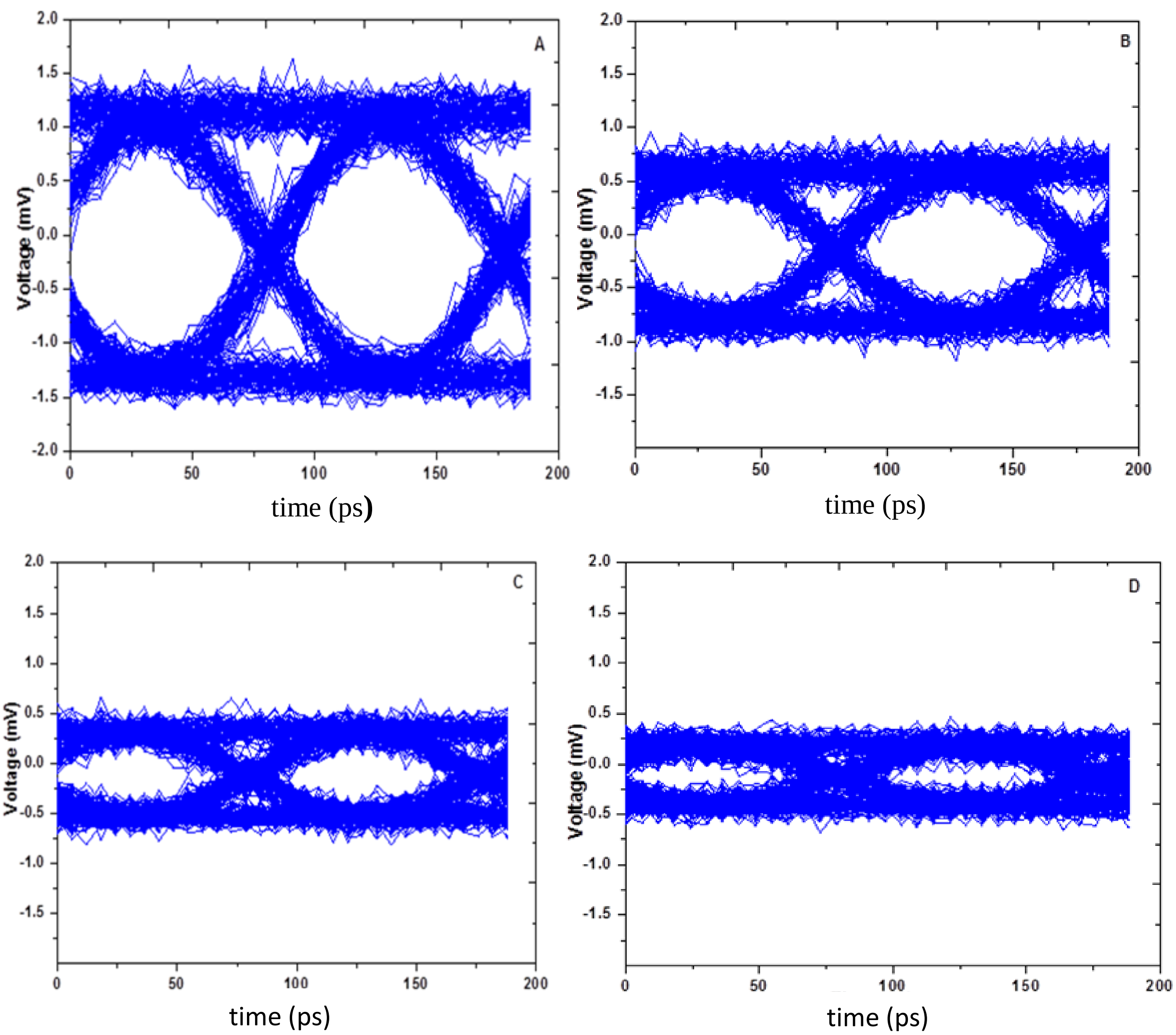


Figure 4.9: DSP eye diagram plots at different power values. [A =- 20.0 dBm, B = - 24.4 dBm, C = - 25.0 dBm, D = - 26.0 dBm]

The slight 1.3 dB improvement in receiver sensitivity could have been attributed to inefficiency in some electrical components such as the electrical amplifier, thereby compromising performance of the commercial BERT. The values of the receiver sensitivity obtained using the two measuring modalities are very close to each other, validating the DSP assisted receiver as a reliable tool to evaluate the performance of any optical communication system.

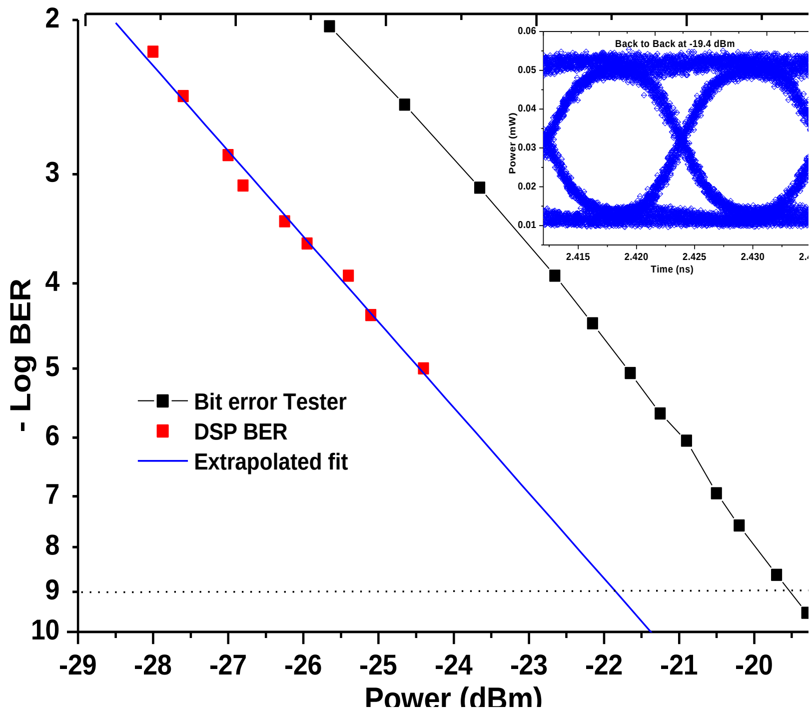


Figure 4.10: BER curves for back-to-back using the commercial BERT and the DSP circuits

The major drawback of the bit for bit measurement technique is that it requires vast amount of memory storage space and is more time intensive. The available sampling oscilloscopes do not have enough storage space for the huge amount of data required to evaluate a high speed optical communication system. It will take a long time to process a billion bits, suitable to meet the ITU standards at a BER of $10^{-9}$.The other drawback is that it is currently done offline and not in real time. In this particular experiment, a total of 200 000 bits were used and an extrapolation was done to evaluate the optical link performance at an acceptable BER of $10^{-9}$.

## 4.8 Conclusion

The two binary modulation formats ASK and DPSK, discussed in this thesis have been practically deployed in some existing optical communication networks. Their varying performance capabilities have enabled them to be implemented in different communication environments. The DPSK format due its higher tolerances to dispersion is mainly suitable for use in long haul optical communication systems. Better performance on short distance transmissions and cost effectiveness on implementation makes ASK format a suitable candidate for use in access networks. The reconfigurable DSP circuits designed and implemented are a reliable tool to evaluate the performance of any optical communication link in the absence of the expensive hardware. Furthermore both ASK and DPSK modulation formats are the primary elements in the architecture of higher order modulation formats which are more spectral efficient [17, 30, 109] and were demonstrated to pave way for a better understanding of higher order modulation formats. The next chapter discusses the different detection techniques that were implemented on an intensity modulated signal. The traditional direct detection technique is compared to the coherent detection scheme. Higher order modulation format will be discussed in the sixth chapter of this thesis.

# Chapter 5

# 5 Amplitude modulation with coherent detection technology in high speed optical communication system

## 5.1 Introduction

The advent of faster digital electronic gadgets and high speed internet access has revolutionized the world into a global village by the ease with which people are communicating. Nowadays, several new and traditional services provider use the internet as a platform to run their business, demanding ever increasing data rates. However, to meet the capacity requirements of the telecommunication market, optical communication systems have been suggested as the most efficient and sustainable solution to transmit at high data rates for both short and long distances. Today's communication networks comprise of several interconnected nodes [114]. Depending on the channel requirements, several modulation technologies can be employed to transmit information and a suitable detection technology is required to demodulate the received bits of information. In this chapter amplitude modulation employing coherent detection is experimentally demonstrated. The first section of the chapter describes the optical signal generator used. The optical receiver was explained in detail with more emphasis on the digital signal processing (DSP) circuits that were designed to low pass filter the signal and eventually evaluate the link performance through bit error ratio (BER) computations. The last section gives a discussion on the comparative performance between coherent detection and direct detection schemes based on simulation and experimental demonstrations. Amplitude modulation employing coherent detection with benefits of increased receiver sensitivity, greater unamplified reach and a greater passive splitting ratio, can be used in most passive optical access networks (PONS), with special focus on the fibre-to-the-hut technology from an African context [45, 63, 91].

## 5.2 Experimental and simulation design

In the preceding sections of this chapter, experiment and simulation results will be presented for intensity modulated system with a coherent detection scheme. Experimental signal generation and detection are briefly explained followed by a detailed description of signal conditioning and reconstruction for link performance evaluation. VPI software was used for simulation.

## 5.3 Signal generation

In today's fast growing technical society, optical communication requirements are broadening rapidly. Different modulation formats have been implemented on different optical networks. The selection of a particular modulation format depends upon the design, available resources and requirements of the network. However high speed with low cost is an indispensable requirement for any reliable optical communication system [115]. Amplitude modulations with direct detection schemes is the dominant, simple, universal and cost effectiveness technology which has recently achieved a transmission speed of around 100 Gbps [44].

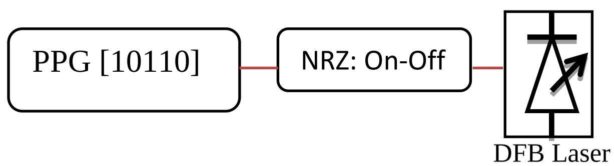


Figure 5.1: Schematic diagram of IMDD transmitter

An efficient semiconductor distributed feedback laser (DFB) directly modulated by the non-return to zero (NRZ) driving current, modifies the amplitude of the optical signal according to the message signal (digital or analog) forms a transmitter in a high speed optical network, as shown in figure 5.1. The temperature controlled DFB laser, shown on Figure 5.1 operating in the 1550 nm transmission window, were the fibre attenuation losses are as low as 0.2 dB/km has an improved performance in a high speed optical communication link. A DFB laser was used in the experimental demonstration described in this chapter as the source of the optical carrier signal.

## 5.4 Signal detection and system performance evaluation

In high speed optical fibre communication systems, the baseband signals are modulated onto one of the four degrees of freedom (DOF), amplitude, phase, frequency and the state of polarization of a high frequency optical carrier pass band signal [11, 12, 38, 43]. Each modulation format must be accompanied with a suitable detection technique to correctly demodulate the transmitted signal. The commonly implemented optical detection methods include non-coherent (direct detection), differentially coherent and coherent detection, as well as some hybrid schemes [46, 91, 94, 116, 117]. Non-coherent detection is mainly associated with On Off keying, in which the receiver computes decision based on a measurement of signal energy. Direct detection technique has a limitation of allowing signals to encode information only on one degree of freedom (DOF) per polarization per carrier, reducing spectral efficiency and power efficiency in the system. Phase modulated signals are demodulated utilizing differential coherent detection technique in which a receiver computes decision variables based on a measurement of phase difference between the symbol of interest and one or more reference symbol(s). Coherent detection demodulates the signal by detecting the entire optical field that is, the amplitude, absolute phase and the state of polarization of the carrier signal making use of the local oscillator laser located at the receiver that acts as a reference signal. However this comes at an expense of increased cost and complexity of the receiver.

Coherent detection has been widely used to demodulate higher order modulation formats [11, 62,109]. In this chapter however coherent detection has been implemented on an amplitude modulated signal.

### 5.4.1 Coherent detection receiver

The most advanced detection method is coherent detection that involves beating in a photodiode the received modulated optical signal with a continuous wave (CW) signal from another laser at the receiver known as the local oscillator (LO). In coherent detection the receiver computes decision variables based on the recovery of the full electric field, which contains both amplitude and phase information of the received signal [54]. Coherent detection allows the greatest flexibility in modulation formats, as information can be encoded in amplitude and/or phase of the carrier signal. The main challenge in coherent detection is that the receiver requires to have knowledge of the carrier phase as the received signal is demodulated by a LO laser that serves as an absolute phase reference [48, 54].

The benefits of a coherent detection scheme includes increased receiver sensitivity, extended unamplified reach, increased network capacity by close wavelength allocation and ability to demodulate advanced modulation formats [36, 45, 48, 63, 118]. Figure 5.2 shows the schematic diagram of a coherent detection receiver with digital signal processing circuits for signal recovery and the optical link performance evaluation.

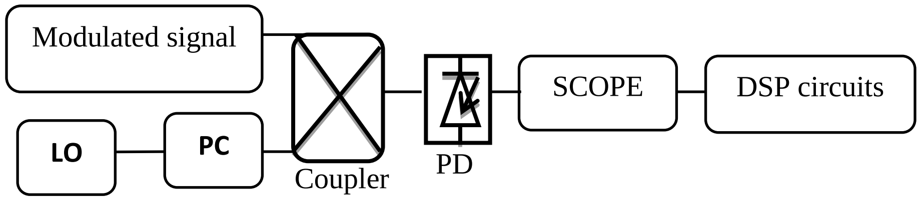


Figure 5.2: Homodyne coherent detection receivers

For amplitude modulation the coherent receiver can be simplified from a convectional 90 degree optical hybrid scheme with two balanced photodiodes to a simpler one with a 3 dB coupler and single photodiode. The cost effective and simplified coherent receiver consists of a single PIN photodiode, local oscillator laser, polarization controller and a 3 dB coupler, as shown in figure 5.2. In the implemented homodyne coherent receiver, the frequency of the LO signal was matched to that of the carrier signal to down convert the pass band signal back to baseband signal. The polarization controller was used to maximize the output of the photodiode by matching the states of polarization of the carrier signal and LO signal. The opto-electrical down converted envelope signal is recovered by passing it through a series of integrated digital signal processing circuits as highlighted in the next sections.

### 5.4.2 Reconfigurable digital signal processing aided receiver circuits

The envelope demodulated signal is passed through a series of separate but integrated DSP circuits for signal recovery and link transmission performance evaluation. Figure 5.3 shows on the same plot the direct detected signal (red) and coherent detected signal (blue).

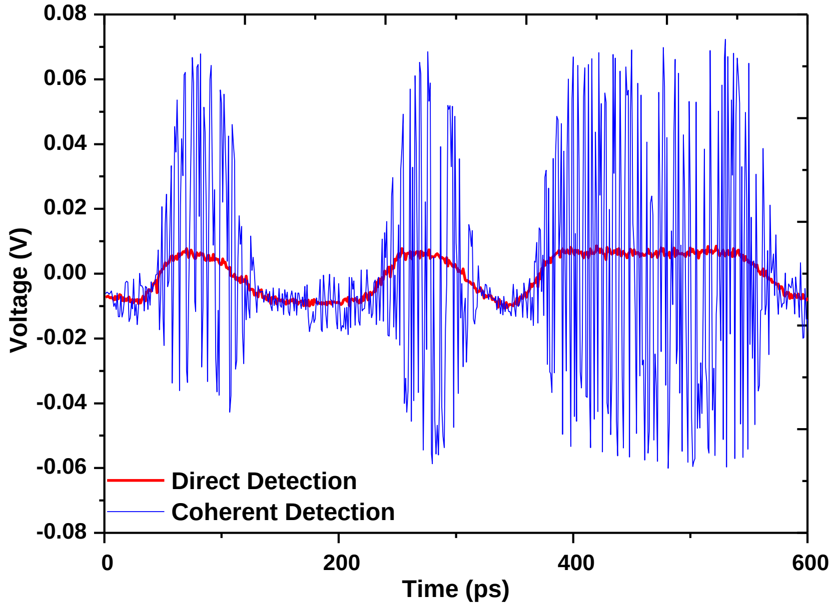


Figure 5.3: Direct detected and coherent detected signals

The envelope of a signal is the outline of the signal and can be obtained by connecting all of the peaks of the coherently detected signal (blue). The envelope of the coherently detected signal will look exactly like the directly detected signal (red) though with an amplified amplitude. To extract the signal envelope, the signal has to be passed through a series of DSP circuits. The first DSP circuit involves centering and squaring the input signal and sending this signal through a lowpass filter. Squaring the signal demodulates the input by converting it from double sided to a single sided signal by eliminating the negative values. This means that half the energy of the signal is pushed up to higher frequencies and half is shifted down toward direct current (DC).

### 5.4.3 Low pass filtering

The next important DSP circuit is the low pass filter (LPF). The squared signal is passed through a lowpass filter to eliminate the high frequency component. A four order moving average low pass filter was designed and implemented in MATLAB according to the following equation.

$$Y_{(n)} = \sum_{i=n}^{4}[X_n + X_{n-1} + \cdots X_M] \qquad [5.1]$$

The filter eliminated all the high frequency components of the signal leaving out only the signal envelope which is the information bearing signal. Figure 5.4 shows the double sided coherently detected signal (blue) together with the filtered signal envelope (green).

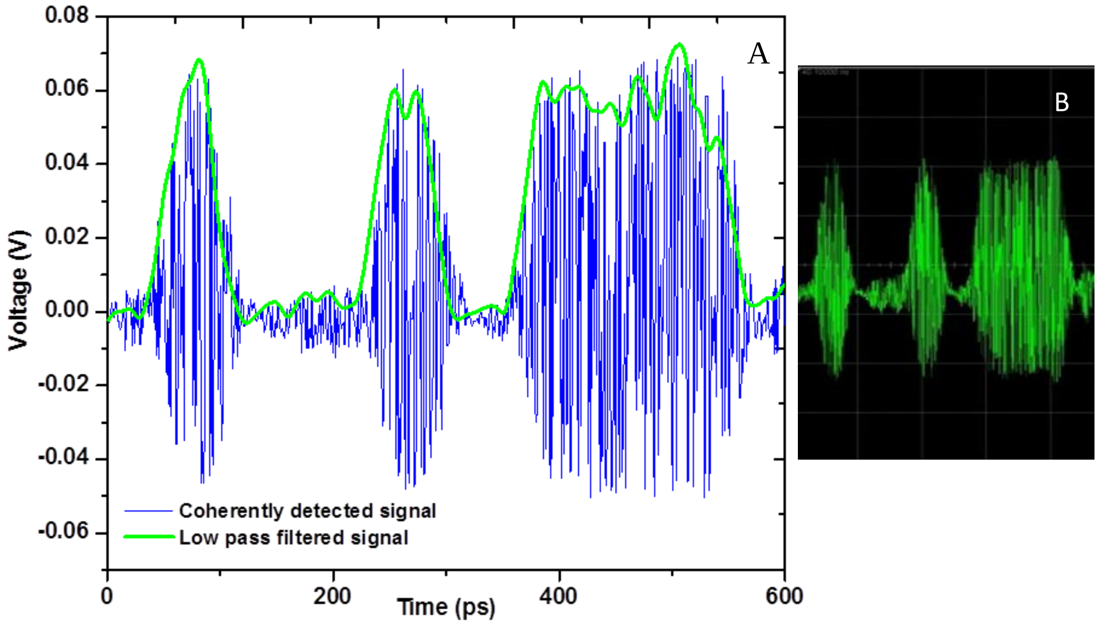


Figure 5.4: Voltage against time graph for coherently detected signal (blue) and filtered smooth signal (green). (b) Screen image of the coherently detected signal.

### 5.4.4 BER Measurements

Bit error ratio (BER) measurement which is an effective and reliable quantitative evaluation technique was used to evaluate the performance of the optical communication link. The BER measurements were computed from the analogue parameters of the filtered signal. To maintain the correct scale on the received signal, two additional operations were carried out on the signal envelope. The signal is first amplified by a factor of two since only the upper half of the signal energy was considered and the amplification gain matches the energy to that of the original signal. Secondly the square root of the signal is computed to reverse the scaling distortions that resulted from squaring the signal. The green signal envelope in figure 5.4 is the end product of the DSP algorithms implemented for signal recovery. The filtered signal has characteristics similar to those of a traditional two level intensity modulation direct detected signal. The Q factor technique was implemented in the determination of the BER. The detailed explanation of the technique is given in chapter 3 and BER was computed using equation [3.24]. The next sections discuss the simulation and experimental results.

## 5.5 Simulation and experimental setup to demonstrate coherent detection

The simulation and experimental set up is shown in Figure 5.5. A programmable pattern generator (PPG) directly modulated a 1550 nm distributed feedback (DFB) at 10.3 Gbps with a non-return-to-zero (NRZ), pseudo random binary sequence (PRBS) of length $2^7$-1.The intensity modulated signal was transmitted through a non-zero dispersion shifted fibre, (NZDSF) with an attenuation co efficient of0.2 dB/km, for a total distance of 26km. The transmitted signal is demodulation at the coherent receiver with digital signal processing aided circuits. The homodyne coherent detection receiver requires that the frequency and phase of the transmitted signal and the LO signal be matched. The LO was wavelength tuned to match that of the transmitted signal at 1550 nm. A polarization controller (PC) was used to align the two signals to give maximum power output at the receiver. A variable optical attenuator (VOA) attenuates and introduces signal losses in the transmission link. The optical power at different attenuation values was measured by the power meter. The 3 dB coupler beats the modulated signal with the LO signal prior to detection and down conversion to an electrical signal by the photodiode. An Agilent oscilloscope was used to sample the transmitted data, which was then transferred to a computer for offline processing using relevant reconfigurable DSP circuits. The DSP envelope demodulator processes the signal ‘U’ by squaring and amplifying before passing it through a low pass filter. The envelope is extracted by removing all the high frequency component of the signal and keeping only the low frequency data carrying signal (envelope). The DSP algorithm was used to plot the eye diagram, which is an intuitive way to access the signal quality. The error detector (ED) was implemented through the Q factor approach which uses the analogue parameters of the smooth filtered signal data to determine the bit error rate (BER) of the optical communication link.

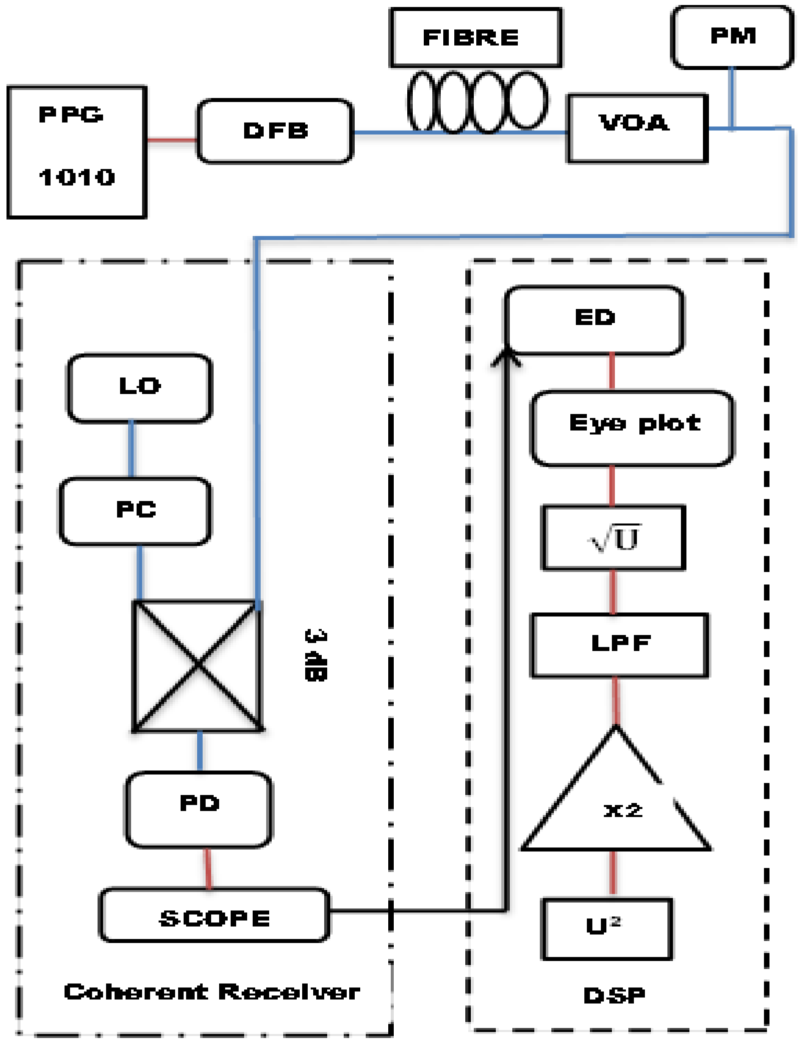


Figure 5.5: Experimental setup for an amplitude coherent detection scheme.

## 5.6 Performance comparison between the traditional intensity modulation direct detection and coherent detection

In this section of the research, a traditional intensity modulated direct detection (IMDD) scheme is compared to intensity modulated coherent detection scheme (IMCD) using VPI simulation software. Coherent detection is a modification of the tradition IMDD by mixing the modulated signal with a continuous wave signal of the same frequency at the receiver. In a homodyne coherent scheme, phase matching of the transmitted signal and local oscillator is of vital importance in enhancing the quality of the signal at the receiver. The receiver sensitivity at an acceptable BER of $10^{-9}$ and the corresponding penalties after transmission through a G. 652 fibre were determined.

### 5.6.1 Simulation results and discussion

For both direct detection and coherent detection, a 3 mW signal is directly modulated with a $2^7$-1, pseudo random bit sequence (PRBS). In an intensity modulation direct detection (IMDD) setup, the signal is transmitted and is detected at the receiver. In a coherent detection scheme a 4 mW LO signal is mixed with the modulated signal before detection by a photodiode. The LO laser used had a narrow linewidth to optimizime the coherence length of the two signals thereby increasing the receiver sensitivity. The beating increases the optical signal power that the receiver gets resulting in improved receiver sensitivity.

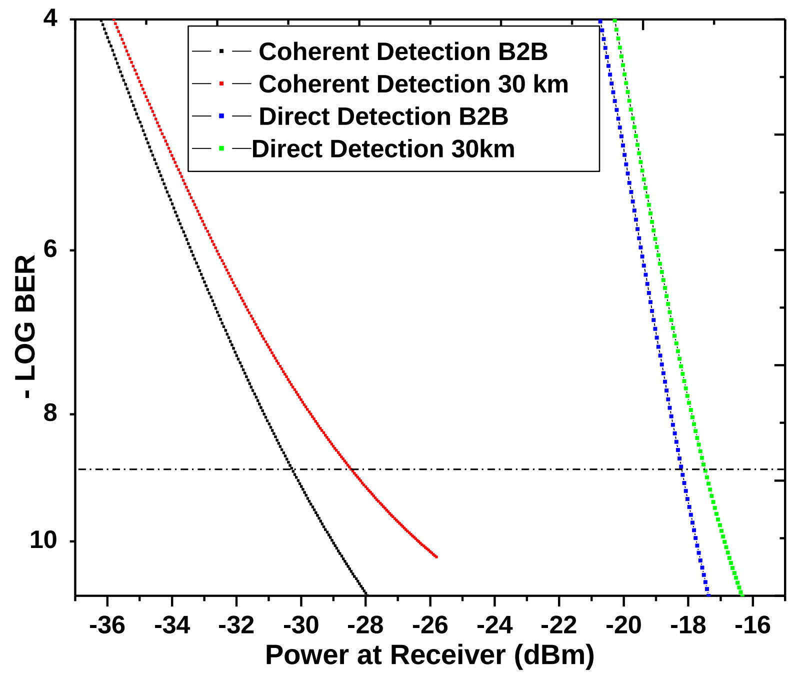


Figure 5.6: Shows the BER curve for back-to-back and a transmission through a 30 km **(**NZDSF) fibre at 1550 nm wavelength.

A receiver sensitivity of -18.3 dBm and -30.4 dBm is obtained for intensity modulated direct detection (IMDD) and intensity modulated coherent detection (IMCD) respectively as shown in figure 5.6. The IMCD has a 12.1 dB gain in receiver sensitivity compared to the IMDD. A penalty of 1.9 dB is obtained for the coherent detection scheme compared to 0.8 dB for direct detection scheme after transmission through 30 km of fibre. Power budget calculations indicate an unamplified transmission distance of 135 km for coherent detection scheme and 75 km for direct detection. The benefits of using coherent detection with an amplitude modulation scheme make it a suitable candidate for application in a passive optical network. If applied in a passive optical network (PON) the power budget gives a splitting ratio of 1:32 and 1:128 for IMDD and IMCD respectively. The higher receiver sensitivity, higher splitting ratio and a long unamplified transmission reach makes coherent detection scheme a technology of choice for application in fibre-to-the-home (FTTH) technology.

## 5.7 Experimental demonstration of intensity modulation coherent detection scheme

The setup described in section 5.5, figure 5.5 was used to experimentally demonstrate intensity modulation with coherent detection. The unavailability of the commercial hardware in our NMMU laboratory to evaluate the transmission performance of a coherent detection scheme has brought about a necessity to develop an offline DSP aided receiver. The developed DSP receiver performance was first implemented with experimental data obtained from the traditional intensity modulation direct detection scheme before implementing it with data from the coherent detection setup. The operational performances of the DSP receiver on the IMDD setup was authenticated and validated by comparing it to the results obtained from a commercial Luceo BER tester. After performance validation the developed DSP receiver was used to monitor and evalaute the transmission performance of a coherent detection setup.

### 5.7.1 Validation of the DSP aided receiver

Experimental back-to-back transmission on a traditional intensity modulation direct detection setup was evaluated using the commericial BER tester and the developed DSP assisted receiver. Comparative BER performance of the two evaluation modalities are as illustrated in figure 5.7.

Figure 5.7 shows BER measurement curves for a direct detection intensity modulation scheme. The black curve is for measurements obtained using a commercial Luceo Bit error ratio tester (BERT) giving a receiver sensitivity of -17.1 dBm. The blue curve was obtained from the developed reconfigurable DSP circuits yielding a receiver sensitivity of -17.2 dBm, with a mere 0.1 dB difference. The measured values of the receiver sensitivity are within the range specified for a positive intrinsic negative (PIN) photodiode. These results were used to validate and authenticate the effectiveness of the reconfigurable DSP circuit as a reliable tool to evaluate the performance of a high speed optical fibre communication system.

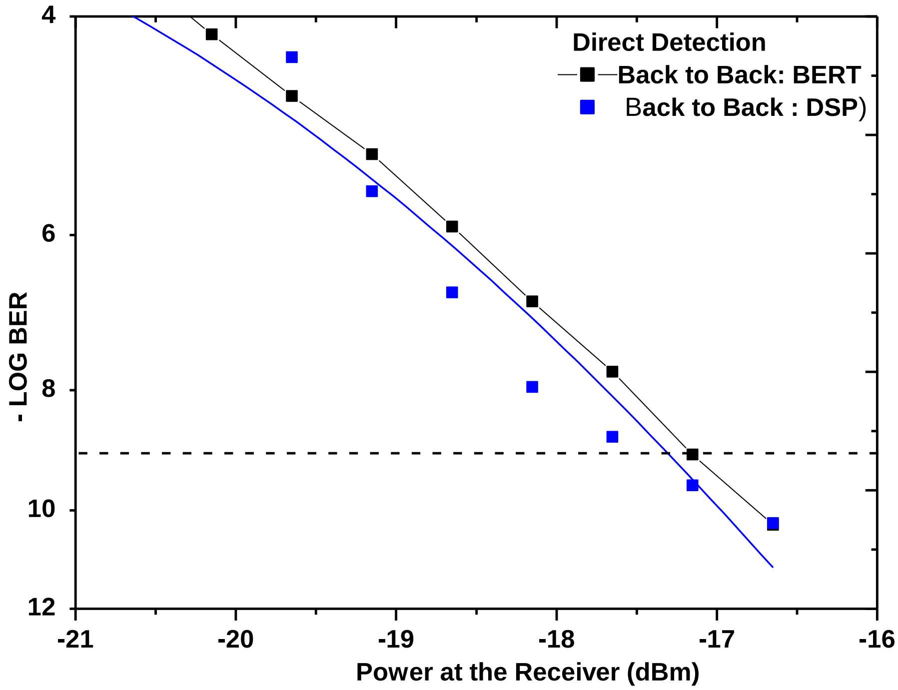


Figure5.7: Back-to-back BER curves for direct detection at different received optical powers. Black curve was obtained from a commercial bit error rate tester (BERT) and the blue from the developed DSP circuits.

In this work two different DSP algorithms we developed and implemented to validate and authenticate the performance of such developed algorithms against the performance of the commercial hardware. Figure 4.10 shows results obtained using an externally modulated Mach-Zehnder modulator and a bit for bit DSP assisted receiver. Figure 5.7 is a similar graph obtained from using an internally modulated distributed feedback laser (DFB) utilizing the quality factor technique to evaluate the link performance. The good quality signal from a MZM coupled to a more accurate bit for bit technique gave a better receiver sensitivity of - 21.2 dBm as opposed to the - 17.1 dBm for an internally modulated signal evaluated using a statistical quality factor method. However the two offline techniques are reliable tools to evaluate the performance of a high speed optical communication link in absence of the expensive hardware.

### 5.7.2 Transmission performance of a coherent detection scheme

A pseudo random bit sequence ($2^7$-1), was transmitted at 10.3 Gbps and was coherently detected as shown in figure 5.5. The data sampled by the Agilent oscilloscope was transferred to the reconfigurable digital signal processing (DSP) circuits that were designed and developed to reconstruct the received signal and evaluate the link performance through BER calculations. The envelope detection DSP involves squaring the signal and passing it through a low pass filter. A fourth order moving average low pass filter was developed and implemented in the DSP algorithm. The filtered, smooth data signal was used to plot an eye diagram, from which the parameters to calculate the BER were determined. Figure 5.8 shows the eye diagram obtained from the two detection schemes.

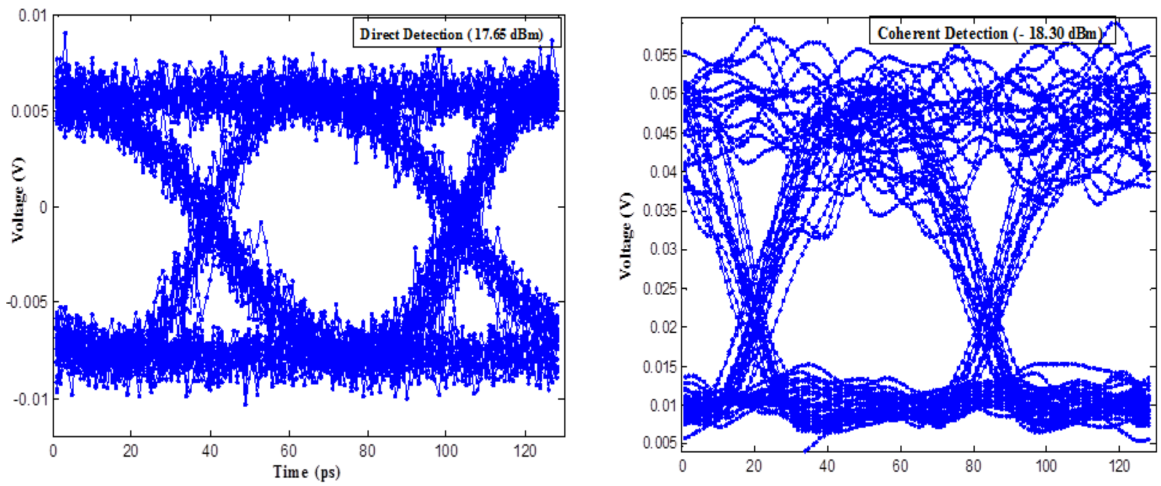


Figure 5.8: Electrical eye diagram plots for traditional intensity modulation and coherent detection

The open eye diagram for the two detection modalities show signals of good quality. The direct detection scheme eye diagram was obtained from the commercial hardware while that for coherent detection was plotted using the developed DSP circuits. The two diagrams have similar characteristics. The eye plot further validates and authenticates the DSP aided receiver as a reliable tool to evaluate a high speed optical communication link.

Results for the transmission performance of a coherent detection scheme are illustrated in figure 5.9. BER measurements for back-to-back and after a transmission through 26 km of (G. 655) fibre in a coherent detection intensity modulation setup are used to establish the transmission penalty. A receiver sensitivity of - 20.6 dBm was obtained for back-to-back transmission giving a penalty of 1.5 dB after transmission through 26 km of fibre.

Figure 5.10 puts everything together by highlighting the comparative performance of the traditional non-coherent (direct) detection and the coherent detection modalities. The figure shows BER measurement curves for back-to-back for both transmission schemes (direct and coherent detection) and for transmission through 26 km of fibre for coherent detection scheme. The graph shows a 3.5 dB gain obtained on comparing back-to-back transmission for coherent detection against the direct detection. As highlighted earlier on, a 1.5 dB transmission penalty was recorded after transmission through 26 km fibre in a coherent detection scheme.

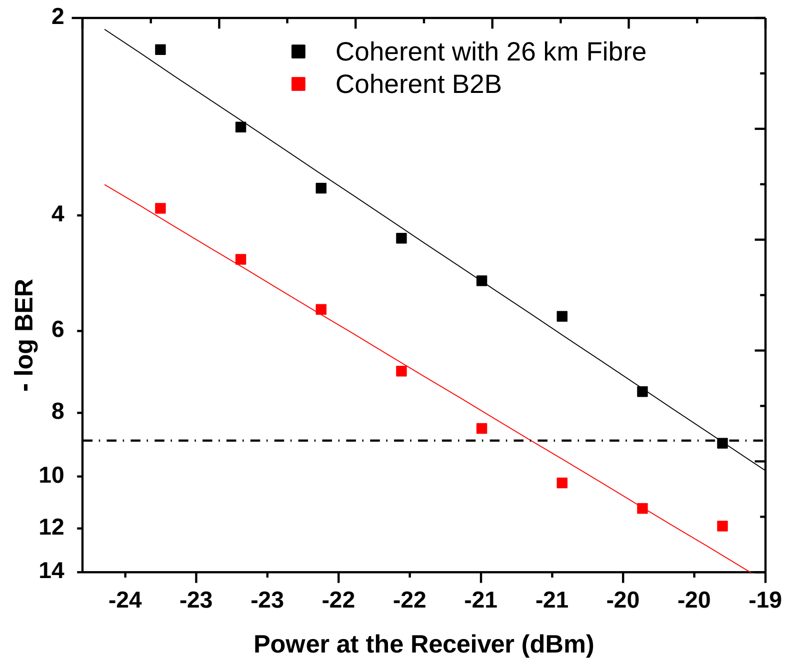


Figure 5.9: BER curves for back-to-back against a transmission over 26 km (G.655) fibre. A transmission penalty of 1.5 dB was achieved

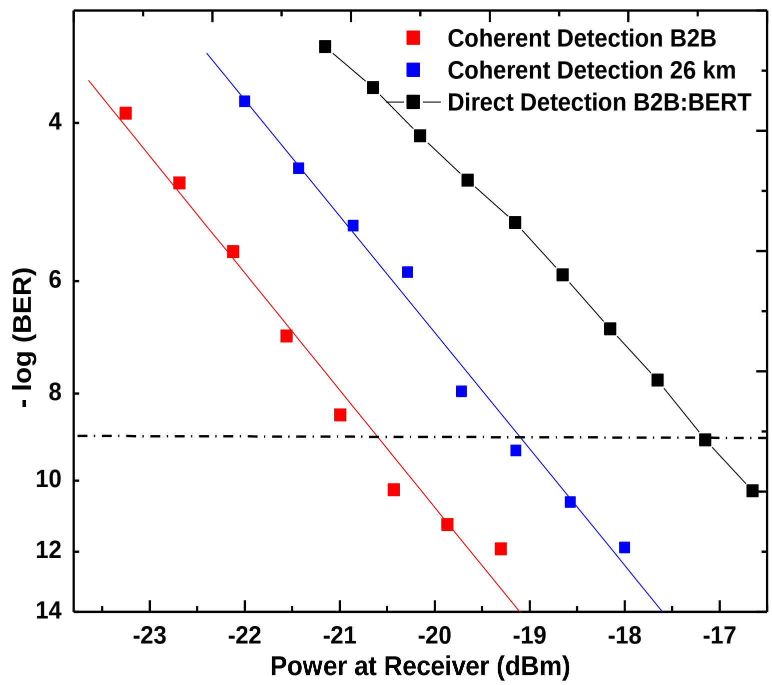


Figure 5.10: BER curves for back-to-back for both direct and coherent detection and for transmission through 26 km of non-zero dispersion shifted fibre, (NZDSF).

## 5.8 Conclusions

The merits of implementing a coherent detection scheme with reconfigurable DSP circuits for performance evaluation over the traditional direct detection scheme were summarized in figure 5.10. The improved receiver sensitivity, the longer unamplified transmission reaches and more bandwidth utilization makes coherent detection a suitable candidate for application in passive optical access networks with special focus in the Fibre-to-the-Home technology. The flexible and reconfigurable DSP assisted signal analyzer is a cost effective way to monitor and evaluate the performance of any high speed optical communication system. Communication industries and research institutions will benefits from using the reliable and cost effective reconfigurable signal analyzer.

The next chapter focuses on a more spectral efficient high order modulation format, that transmit two bits per symbol. The higher order 4 Pulse Amplitude Modulation (4-PAM) format was also evaluated using the developed DSP algorithms.

# Chapter 6

# 6 Multilevel pulse amplitude modulation format with digital signal processing aided receiver

## 6.1 Introduction

The ever increasing demand for bandwidth requires the use of higher modulation formats which are more spectral efficient compared to the traditional modulation formats. This chapter describes a quaternary intensity modulation technique. The generation and detection scheme for the higher modulation format will be explained in detail, with an evaluation of its performances based on experimental results. A 20 Gbps transmission link was demonstrated from 2 x 10Gbps transmitter. The bit error ratio (BER) link performance was computed using the designed digital signal processing (DSP) assisted receiver. The main objective of the experiments demonstrated in this chapter is not to compete in transmission speeds, but to find cost effective and more spectral efficient modulation formats that achieve higher data rates without changing the form, nature and channel bandwidth of already deployed optical communication networks

## 6.2 Experimental design

The following sections describe a technique that was used to generate a multilevel signal that was used to modulate the optical signal. The demodulation process is explained in detail followed by a presentation of the experimental results.

## 6.3 Multilevel pulse amplitude modulation (PAM) format

Traditional binary intensity modulation formats is a two level amplitude shift keying (ASK) technique in which the signal levels are switched between ‘0’ and ‘1’. Multilevel pulse amplitude modulation or intensity modulation is a more spectral efficient technique in which more levels are assigned to the amplitude of the signal [6, 10, 33, 119]. Each amplitude level is assigned two bits of information. The number of bits ‘m’ transmitted per symbol determines the number of levels ‘M’ the signal can have as given by equation $M = 2^m$. In this chapter, a system with two bits (m = 2) per symbol resulting in an 4–ary ASK signal is demonstrated. The quaternary (4-ary) signal will be referred to as a 4 level pulse amplitude modulation (4-PAM) or 4 level intensity modulation (4-IM) signal. The multilevel 4-PAM electrical signal was used to drive the internally/directly modulated distributed feedback (DFB) laser generating a 4 level amplitude modulated optical signal. The performance of the developed multilevel high speed optical communication system could not be directly evaluated using the available hardware at the NMMU Centre for Broadband Communication. However a digital signal processing (DSP) assisted receiver was developed and implemented to evaluate the link performance through bit error ratio calculation for the multilevel signal [11, 120, 121].

The developed 4-PAM optical communication system is a cost effective innovation for it uses both optical and electrical components operating at half the system bit rate compared to the bit rate of a traditional binary modulation format. A 20 Gbps optical communication system was developed from a 2 x 10 Gbps. The multilevel transmitter and its accompanying DSP assisted receivers are explained in the sections to follow.

### 6.4 Multilevel (4- PAM) signal generation

Two complementary (P and N), 10 Gbps non-return-to-zero (NRZ) electrical signals generated from a single programmable pattern generator (PPG) were used to output a 20 Gbps, 4-PAM signal. The transmitted quaternary optical single can be obtained by internally or external modulating the laser carrier signal with the 4-IM electrical signal. The 4-ASK electrical signal was achieved by combining two NRZ binary signals with different amplitudes in an electrical power combiner. The two electrical outputs were differentially attenuated to generate two binary data streams of different amplitudes. To achieve uniform eye opening, the attenuation value in one arm should be double that in the other arm. The complementary signals were decorrelated by propagating them through different path length (delay) as shown in figure 6.1.

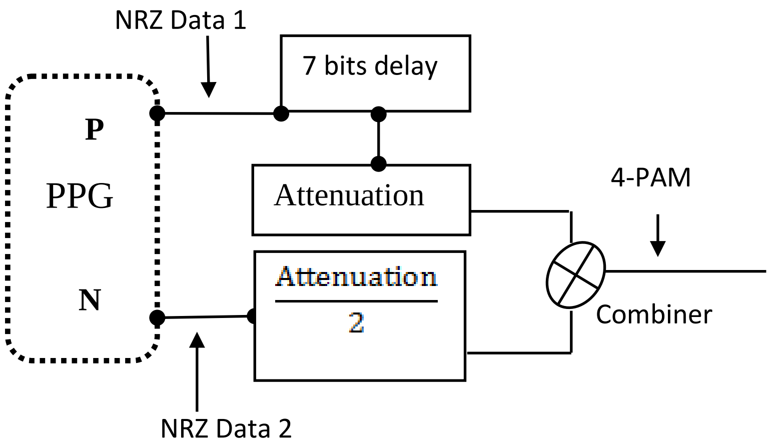


Figure 6.1: Multilevel 4-PAM electrical signal generators: Programmable pattern generator), N- negative and P-positive outputs)

The 4-PAM electrical signal was achieved by combining the two differentially attenuated and decorrelated 10 Gbps NRZ signals in an electrical power combiner. The eye diagram shown in figure 6.7 is the resultant multilevel 20 Gbps NRZ signal.

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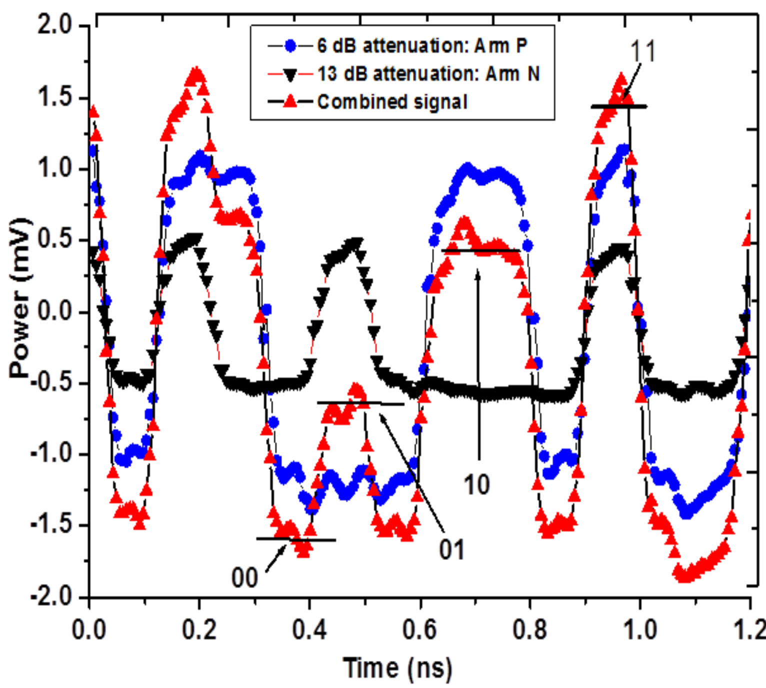


Table 6.1: Mapping of input binary data on 4 levels for a 4-PAM signal

| | Input Data | |
|---|---|---|
| **Symbol** | **Data 1** | **Data 2** |
| $S_0$ | 0 | 0 |
| $S_1$ | 0 | 1 |
| $S_2$ | 1 | 0 |
| $S_3$ | 1 | 1 |

Figure 6.2: Resultant output 4-PAM (red) signal, individually attenuated (black and blue) waveforms and the corresponding input data bits mapped on signal symbols as shown table 6.1

Figure 6.2 and table 6.1 shows the mapping of the input data stream on the output four levels of the signal. The black and blue waveforms are for the differentially attenuated signals before mixing them in the power combiner. The red waveform is the combined four level (4-PAM) signal with the data bits mapped to their respective symbols.

To minimize errors on practical implementation, the mapping of the input data should be guided by the principle of adjacency, where there is only a single variable change on adjacent data symbols [6, 33]. The adjacent mapping is also known in literature as Gray coding. In the event of an error on a Gray coded system, only one of the two bits per symbol will be wrongly detected.

## 6.5 Multilevel (4-PAM) signal detection

The increase in spectral efficiency attained by transmitting a 4-IM signal comes with complexity on the design of the receiver. The transmitted multilevel signal was detected using a single photodiode drastically reducing the implementation cost. In this direct detection scheme the optical quaternary intensity modulated signal is converted back to a 4-PAM electrical signal. The received electrical signal has three eyes corresponding to four data symbols. The three eye diagrams correspond to three different data patterns. The bits are demodulated at the receiver using the designed intelligent decoding circuits that makes a decision based on the three decoding threshold levels [$T_1$, $T_2$and $T_3$]. Appropriate decoding algorithms were developed to map the three eye patterns and the four levels to the two transmitted data streams. The receiver also has to implement a digital clock recovery algorithm to recover the transmitter clock and apply symbol decision at proper sampling instants. Figure 6.3 shows the 4-IM receiver structure, the corresponding decision thresholds and signal symbols with data bits mapped on them.

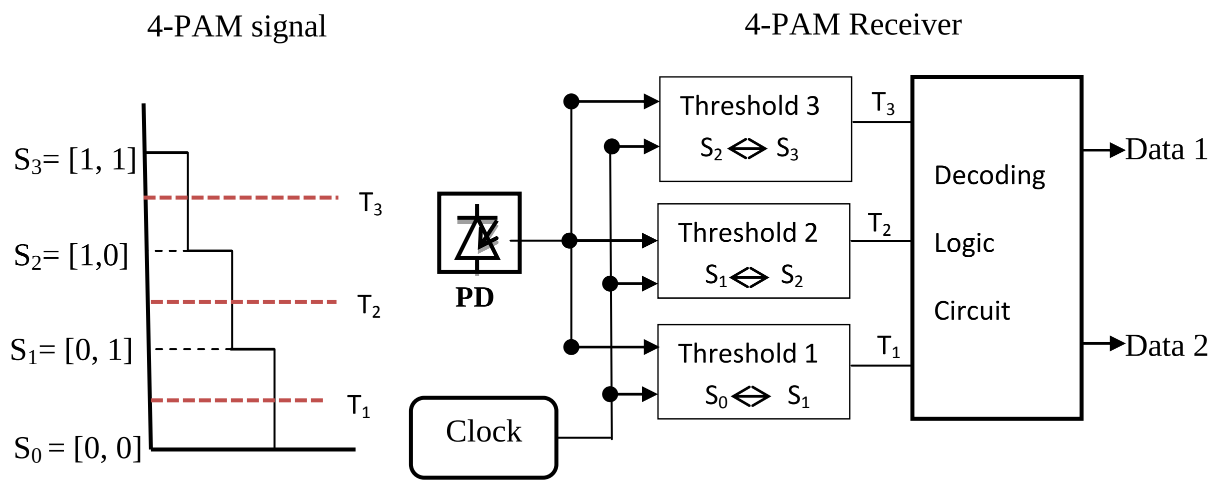


Figure 6.3: Four PAM receiver structure (right) and four signal symbols mapped with appropriate data bits (left).

A single photodiode was used to detect and convert the quaternary optical signal to a corresponding quaternary electrical signal. The decoding logic circuit was developed basing on the three decision threshold values [$T_1$, $T_2$, and $T_3$]. Table 6.2 shows a truth table with three decision thresholds values that were used to logically decode the received signal into its symbols prior to mapping the bit to their respective output data streams. Using logic Karnaugh mapping technique, the decoding logic circuit in figure 6.4 was deduced and implemented from the truth table, shown on table 6.2 on the same figure.

Table 6.2: Truth table for the decoding logic circuit

| $T_1$ | $T_2$ | $T_3$ | $D_1$ | $D_2$ | S |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | $S_0$ |
| 0 | 0 | 1 | x | x | x |
| 0 | 1 | 0 | x | x | x |
| 0 | 1 | 1 | x | x | x |
| 1 | 0 | 0 | 0 | 1 | $S_1$ |
| 1 | 0 | 1 | x | x | x |
| 1 | 1 | 0 | 1 | 0 | $S_2$ |
| 1 | 1 | 1 | 1 | 1 | $S_3$ |

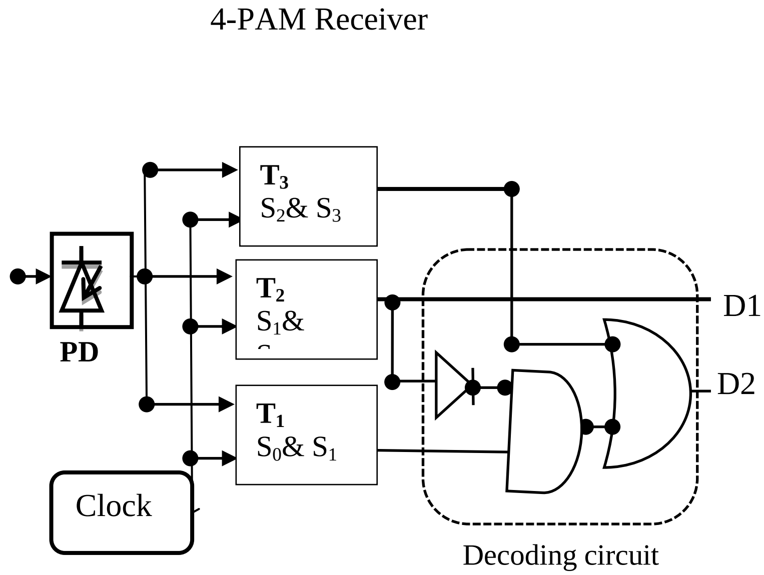


Figure 6.4: Truth table and receiver decoding circuit for 4 – PAM signal

The performance of the 4-PAM high speed optical communication system was evaluated in the software domain, by implementing the above logic circuit with its equivalent digital signal processing (DSP) circuits. The digital signal processing (DSP) aided receiver was implemented using the statistical quality Q factor technique that utilizes the analogue parameters of the signal to give the digital performance of the high speed optical communication system. The details of the technique were explained in chapter three of this thesis. The BER rate performance of the high speed optical communication link was determined using equation [3.26], after gathering the relevant statistical information from the received signal.

## 6.6 Experimental demonstration of a 2 x 10 Gbps (20 Gbps) multilevel modulation format

The schematic diagram shown in Figure 6.5 is a complete multilevel optical transmission link comprising of an electrical transmitter, the medium and the optical receiver. The complimentary, P and N, arms of the programmable pattern generator (PPG), generates the pseudo random bit sequence (PRBS),($2^7$-1), which after combining directly modulates the (DFB) laser. The different electrical attenuations on the two outputs guarantee the existence of two data signals with different power levels (different amplitudes). The N output attenuated at 13 dBm has the electrical data sequence delayed in time by an integer multiple of a bit period, decorrelating the two complemented bit sequences. On mixing in the power combiner, the two decorrelated data sequences interfere constructively and destructively, producing a four level data signal (4-PAM). The mixing doubles the transmission data rate from 10 Gbps to 20 Gbps. The multilevel transmitter therefore codes two bits in one symbol prior to modulation and transmission through the fibre.

The DFB laser signal at 1550 nm is directly modulated at a bit rates of 20 Gbps by a non-return-to-zero (NRZ) pseudo-random binary Sequence (PRBS) signal and is transmitted through a back-to-back and through 25 km single mode fibre. The power meter (PM) measures the optical power at the back end of the receiver after the optical signal power has been attenuated by a variable optical attenuator (VOA). The direct intensity modulated signal is directly detected (DD) by the photodiode (PD). The photodiode (PD) demodulates and converts the quaternary optical signal back to a quaternary electrical data signal. The front-end of the receiver comprises of an oscilloscope that captures and stores the received signal. The captured data is transferred to an offline digital signal processing (DSP) circuit. An Offline digital signal processing algorithm was developed to perform the decoding role of the logic circuit in figure 6.4. The DSP aided receiver was also implemented to monitor and evaluate the overall performance of the designed high speed multilevel optical communication link.

The developed DSP analyzer utilizes the loaded eye data information from the oscilloscope as the input data. Three optimum threshold values are accurately determined thereby demodulating the four signal symbols generated at the transmitter. Mean peak to peak voltage for zero and one level of each of the three eyes is calculated together with their respective standard deviations. The Q factor is calculated from the mean peak to peak voltages as given in equation [3.19] and the standard deviations are computed from the statistical analogue data. The final and most important DSP stage is the determination of the BER values using the calculated Q factor.

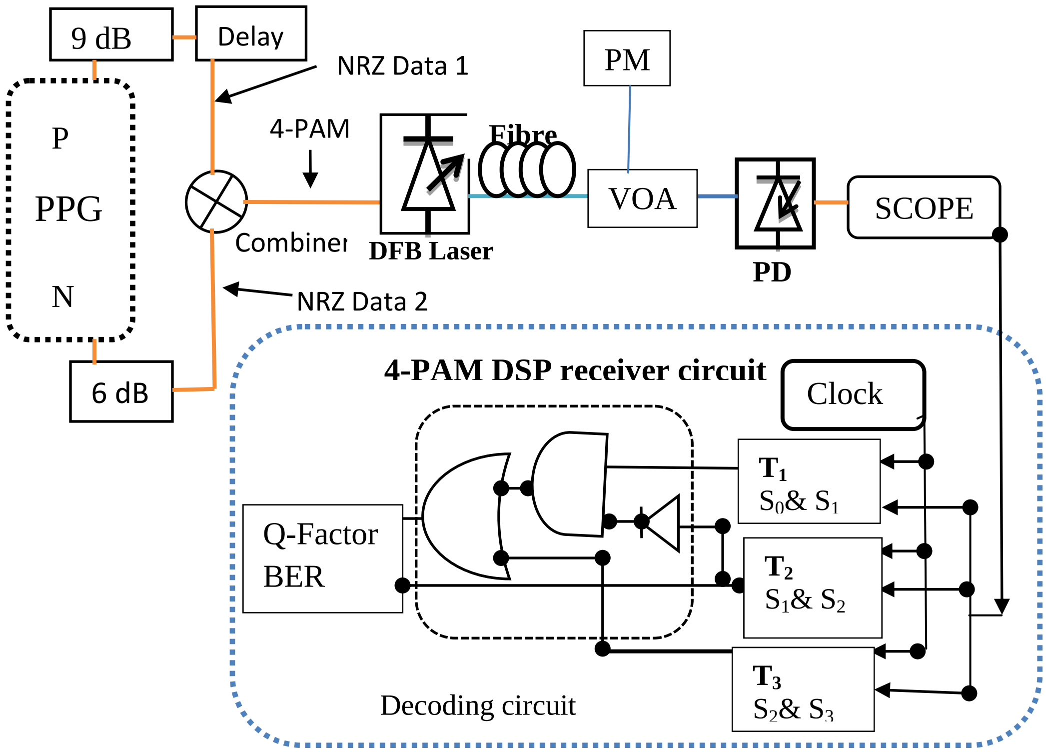


Figure 6.5: Experimental setup for 4 –PAM

Two decorrelated P and N pseudo random bit sequences ($2^7$- 1) each at 10 Gbps are differentially attenuated before combining and doubling the transmission data rate to 20 Gbps. Fig 6.2 shows the individual P and N signal before mixing and the combined signals after mixing. After mixing each of the four symbol comprises of two bits each (00; 01;10 or 11). The graph clearly shows that the combined signal (red) is a result of the interference of the two individual signals (blue and black).

The performance of the multilevel high speed optical communication system was evaluated through BER calculation at the standard acceptable BER of $10^{-9}$. Figure 6.6 shows the experimental BER curve for back-to-back transmission obtained using the statistical probability density function (pdf). The technique uses the analogue information from the signal (Q factor) to accurately estimate the BER performance of the link. A receiver sensitivity of -12.47 dBm for back-to-back transmission was achieved; yielding a penalty of 7 dB compared to a traditional binary modulation reported in chapter 4of this research work. Similar results for a back-to-back transmission were reported in previous studies using a Mach-Zehnder modulator and gave a receiver sensitivity of -13 dBm [6]. The higher penalty in the 4-PAM compared to the binary system was brought about by modulating additional bits within the same modulation depth prompting the need for a more sensitive receiver to demodulate the two bits per symbol.

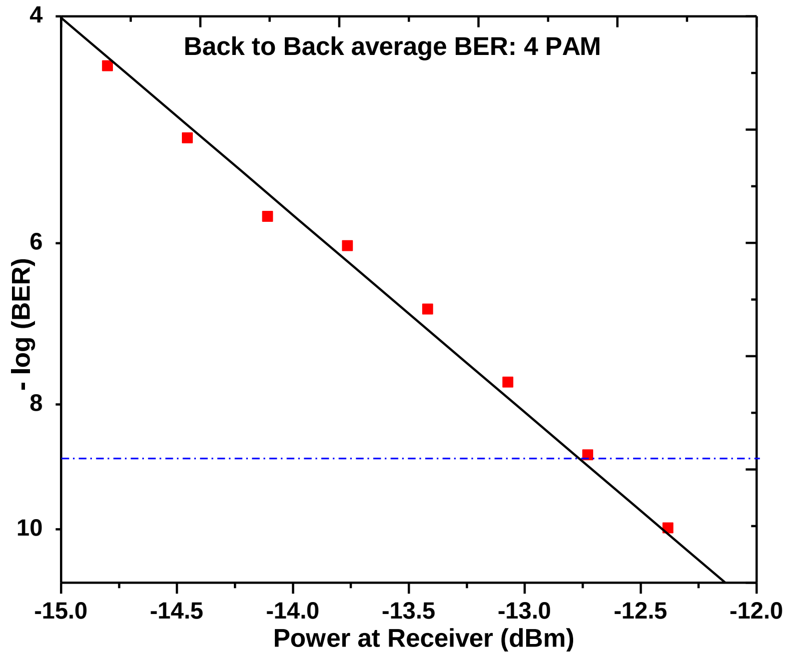


Figure 6.6: Experimental average BER measurements for 4 PAM for back-to-back transmission

On the experimental setup the same peak to peak modulation voltage that was used for a two level system was further divided to accommodate the 4-level system, resulting in a significant reduction in the extinction ratios for each of the three eye diagrams. The reduction in peak-to-peak voltage for each eye diagram means a more sensitive receiver is needed to demodulate the 4-PAM signal.

Figure 6.7 shows the open eye diagrams at different receiver powers of -11.88 dBm and - 13.35 dBm respectively. The diagram has three open eyes and four signal levels. The open eye at -11.88 dBm signifies the signal clarity. However eye closer at -13.35 dBm indicates signal loss due to attenuation effects within the transmission link.

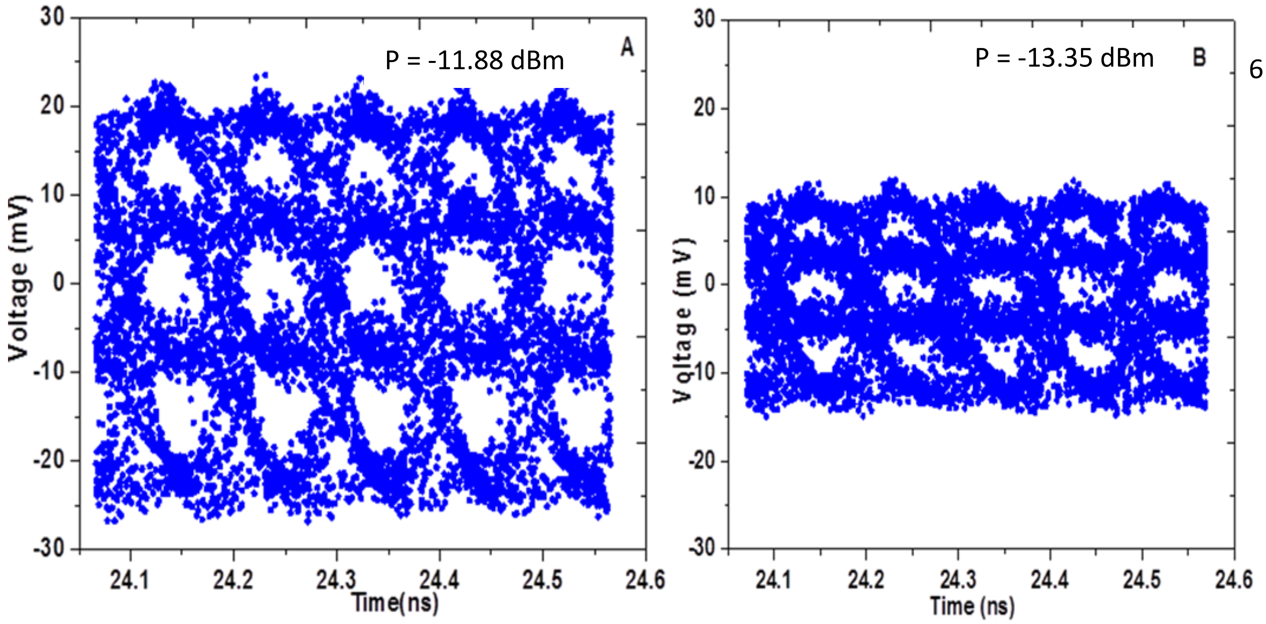


Figure 6.7: Eye diagrams at different receiver powers.

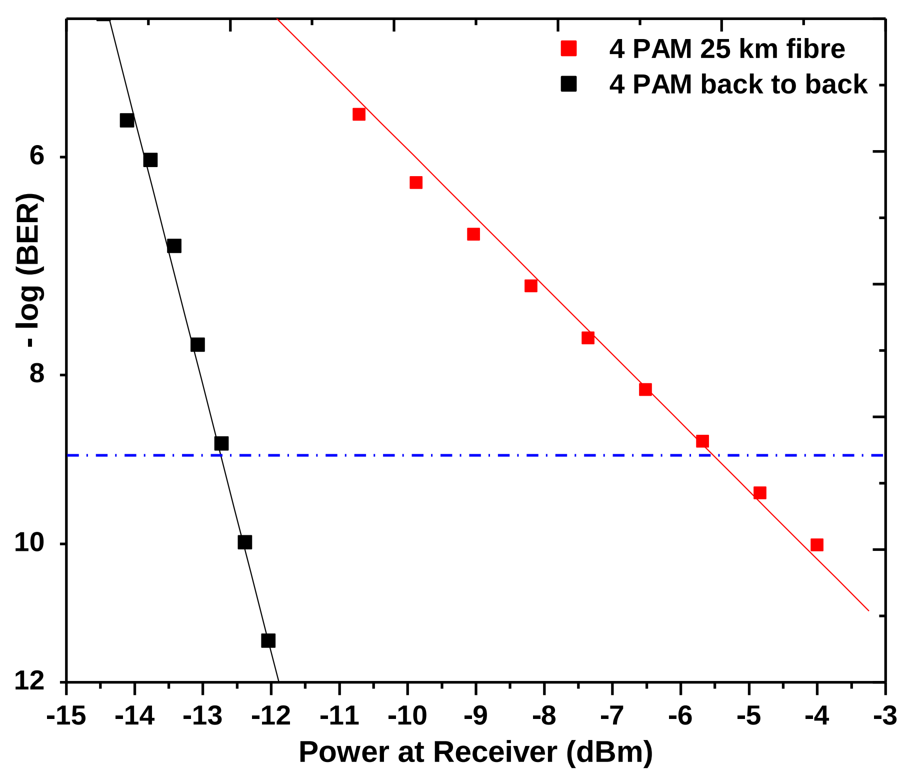


Figure 6.8: Experimental average BER measurements for back-to-back and after transmission in 25 km G.652 fibre

In figure 6.8 a comparative performance through BER measurements is shown for back-to-back and a transmission length of 25 km. A PIN photoreceiver was used in the 4-PAM signal measurements. A receiver sensitivity of - 2.8dBm is attained with a dispersion penalty of about 7.2 dB after transmission through 25 km of G.652 fibre.

The reported BER values in this chapter are actually the average BER values as measured from each of the three eyes diagrams shown in figure 6.7. The eye diagrams could not be adjusted to be of the same size and as a result they performed significantly differently at the same received optical power compromising the overall system evaluation. As seen from figure 6.7 the bottom eye is wide open as compared to the middle and top eye. However despite the slight difference in eye openings the developed DSP techniques gave good results and will be useful in evaluating the performance of a high speed optical network.

## 6.7 Conclusion

The devised higher order modulation technique can be suitably applied to the already deployed optical communication link by only modifying the transmitter without affecting the deployed fibre. The designed multilevel transmitter can be used to simultaneously transmit two bits per symbol per wavelength thereby increasing the overall link transmission speed maintaining the channel bandwidth. The DSP algorithm developed, using the PDF and Q factor is an attractive technology to evaluate and monitor the performance of a high order modulation scheme in the absence of the relevant hardware. In this chapter a four level signal transmitter and detector have been successfully implemented. The multilevel transmitter and the offline signal analyser designed and experimentally implemented are technologies that can help alleviate the ever growing demand for transmission speed in many optical interconnects and local area networks. The developed multilevel DSP algorithms signal analyser can be used in any M-ary modulation formats thereby promoting a cost effective way of evaluating the performance of any high speed optical communication link. The offline DSP receiver with its ability to be reconfigured is a suitable candidate for use in optical communication industries and in research institution.

# Chapter 7

## Conclusions

The work covered in this thesis provided in depth information in understanding the design and implementation of a high speed optical communication system. The main goal of the thesis was to design a higher order modulation format and to develop a signal analyzer tool to evaluate the fidelity of the entire link. A cost effective 20 Gbps multilevel system (4-IM) was successfully designed by combining two electrical data streams at half the bit rate, as compared to a more expensive single optical transmitter that operates at that same speed. The ability to use a single photodiode to demodulate the multilevel signal brings a further reduction in cost on implementing the scheme. This more spectral efficient modulation format will achieve even higher data rates per channel when coupled in a dense wavelength division multiplexed (DWDM) system.

The digital signal processing (DSP) aided signal analyser that was developed for the first time at the Centre for Broadband Communication (CBC) research unit, at Nelson Mandela Metropolitan University (NMMU) is quite an important tool in monitoring the quality of the signal. The reconfigurable digital signal processing aided receiver has proved to be an accurate and reliable tool in analyzing the performance of high speed optical communication links. The ability of the DSP aided receiver to evaluate signals from the different higher modulation formats makes it the suitable candidate for implementation in most future high optical communication networks. The increase in speed and decrease in prices of the DSP electronics makes the reconfigurable DSP aided receiver a tool of choice for optical communication research institutions that cannot afford the high cost of the signal analyzer hardware.

Two optical detection techniques were studied in this thesis, direct detection and coherent detection. Coherent detection which is normally implemented using an expensive optical hybrid was successfully demonstrated using cost friendly 3 dB optical combiners. The benefits of improved receiver sensitivity, larger unamplified transmission reach and higher passive optical splitting ratio makes coherent detection scheme a candidate for application in a passive optical access network (PON), in a fibre-to-the-hut technology in an Africa context.

The results obtained in these experimental demonstrations will give an optical network designer a well informed decision on the modulation format and detection technique that will suit a particular network. The difference in the maximum achievable transmission reach between these different modulation types clearly reflects the importance of the different trade-offs that should be taken into account when choosing a certain data rate and a certain modulation format. These trade-offs include spectral efficiency (SE), optical signal to noise ratio (OSNR) requirements, tolerance to nonlinear transmission impairments and the complexity of the transceiver.

# Appendix A

## Research Output in journals, Conferences and other reports

## Journal manuscripts under review and in preparation

1. **T. V. Chabata**, D. Kiboi , E. K. Rotich Kipnoo, R. R. G. Gamatham, A. W. R. Leitch and T. B. Gibbon. "Reconfigurable Signal Analyzer for Performance Monitoring in High Speed Intensity Modulation Coherent Detection Optical Communication Systems" (*submitted to African review of Physics Journal)*

2. **T. V. Chabata[1]**, D. Kiboi Boiyo[1], E. K. Rotich Kipnoo[1], R. R. G. Gamatham[2], A. W. R. Leitch[1],and T. B. Gibbon[1] "Signal Monitoring and Performance Stability evaluation tool in a High Speed Optical Communication Network" (*submitted to Optik Journal of science", January 2016)*

## Published/accepted/presented articles

## Year 2015:

1. **T. V. Chabata**, D. Kiboi Boiyo, E. K. Rotich Kipnoo, R. R. G. Gamatham, A. W. R. Leitch and T. B. Gibbon, "Directly Modulated 10.3 Gb/s Coherent Detection Scheme for Passive Optical Access Network in the Fibre-to-the-Hut Technology". *Proc of the 18$^{th}$ annual Southern African telecommunication networks and application conference, (SATNAC), Arabella Hotel, Hermanus, South Africa's 6$^{th}$ -9$^{th}$ September 2015.*

2. **T. V. Chabata**, D. Kiboi Boiyo, E .K. Rotich Kipnoo, R. R. G. Gamatham, A. W. R. Leitch, T. B. Gibbon, "Performance Comparison between the Traditional Intensity Modulation Direct Detection and Coherent Detection in a High Speed Optical Fibre Communication System",. *"Presented at the 60$^{th}$ annual conference of South African Institute of Physics (SAIP), Nelson Mandela Metropolitan University, the Boardwalk Convention Centre, Port Elizabeth, 29$^{th}$ June- 3$^{rd}$ July 2015.*

3. D. Kiboi Boiyo, **T. V. Chabata**, E.K. Rotich Kipnoo, R.R.G. Gamatham, A.W.R. Leitch and T.B. Gibbon, "Crosstalk Penalties in Optical Transport for Next-Generation Flexible Spectrum Networks*".(Proc of the 18th annual Southern African telecommunication networks and application conference, (SATNAC), Arabella Hotel, Hermanus, South Africa's pp 6th -9th September 2015.*

4. D. Kiboi Boiyo, **T. V. Chabata**, E. K.Rotich Kipnoo, R.R.G. Gamatham, A. W. R. Leitch and T. B. Gibbon, Reconfigurable wavelength selective switching for 10 Gbps optical fibre ring networks", "*Presented at the 60th annual conference of South African Institute of Physics (SAIP), Nelson Mandela Metropolitan University, the Boardwalk Convention Centre, Port Elizabeth, 29th June- 3rd July 2015.*

**Year 2014:**

1. E. K. Rotich Kipnoo, **T. V. Chabata**, R. R. G. Gamatham, A. W. R. Leitch and T. B. Gibbon, "Experimental Demonstration of Raman Amplification in Vertical Cavity Surface Emitting Lasers for Extended Reach Access Networks" *Proc. of the 17th annual Southern Africa Telecommunication Networks and Applications Conference (SATNAC), Boardwalk-Port Elizabeth, South Africa, pp. 21-24, 31st Aug to 3rd Sept 2014.*

2. **T. V. Chabata,** E.K. Rotich Kipnoo, R. R. G. Gamatham, A. W. R. Leitch, and T. B. Gibbon. A single DFB laser for multilevel directly modulated signal for high speed optical fibre communication system",.*"Proc. 59th Annual Conference of the South African institute of physics (SAIP), University of Johannesburg, 7-11th July 2014.*

3. **T.V. Chabata**, E. Rotich, R.R.G. Gamatham, A.W.R. Leitch, and T.B. Gibbon, "A higher order modulation format for 20 Gbps in a high capacity optical communication system".*Proc. 7th African Laser Centre (ALC) Annual Workshop and 3rd Moroccan Days on Nanoscience and Nanotechnology (MDNN3), MAScIR, FSR –UM5, Rabata – Morocco. 3 -5 Nov 2014.*

**Year 2013:**

*1.* **T. V. Chabata**, R. R. G. Gamatham, H. Y. S. Kourouma, E. K. Rotich Kipnoo, A. W. R. Leitch, and T. B. Gibbon, "Digital Signal Processing Algorithm for Signal Analysis and Performance Monitoring in an Optical Communication Link.*"Proc. 58th Annual Conference of the South African institute of physics (SAIP), University of Zululand, 8-12th July 2013.*

2. **T.V. Chabata**, R.R.G. Gamatham , H. Y. S. Kourouma, E. K. Rotich Kipnoo, A.W.R. Leitch, and T.B. Gibbon, "Digital Signal Processing Algorithm for Signal Reconstruction and Performance Measurement for a Single Photo-detector Optical Communication System". *Proc. 16th annual Southern Africa Telecommunication Networks and Applications Conference (SATNAC) Spiers, Stellenbosch, Western Cape, South Africa 1-4th Sept 2013.*

*3.* E. K. Rotich Kipnoo, H. Kourouma, **T. V. Chabata**, R. R. G. Gamatham, A. W. R. Leitch and T. B. Gibbon, "Optimizing VCSEL Transmission for Longer Reach in Optical Access Networks".*Proc. 16th annual Southern Africa Telecommunication Networks and Applications Conference (SATNAC) Spier, Stellenbosch, Western Cape, South Africa 1-4th Sept 2013.*

4. **T.V. Chabata**, E. Rotich, R.R.G. Gamatham, A.W.R. Leitch, and T.B. Gibbon, "Digital signal processing (DSP) procedures for an externally modulated laser carrier signal in a direct detection optical communication link''. *Proc. 6th African Laser Centre (ALC) Student Workshop, Zevenwacht Stellenbosch, Western Cape, South Africa 21-23th Nov 2013. (**The second best PhD presentation award**)*

**Year 2012**

1. **T.V. Chabata**, E. Rotich, R.R.G. Gamatham, A.W.R. Leitch, and T.B. Gibbon "Performance comparison of OOK, NRZ and DPSK modulation formats in an optical transmission system", *Proc. 5th African Laser Centre (ALC) Student Symposium, University of Namibia, Windhoek ,Namibia 14 -18th Nov 2012.*

## Bibliography


1. M. S. Alfiad, Multilevel modulation formats for robust long haul high capacity transmission, in Electrical Engineering. 2011, Eindhoven University of Technology.

2. D. J. Richardson, J. M. Fini and L. E. Nelson, Space-division multiplexing in optical fibres. Nature Photonics, 2013. Vol. 7**.** p:354-362.

3. S. Garg and A. Agarwal, Performance analysis of DWDM system with different modulation techique and photodiode. International Journal of Engineering and Science (IJES), 2013. Vol. 2**.** pp: 07-11.

4. S. Randel, T. Koonen, J.Y. Lee and F. Breyer, Advanced modulation techniques for polymer optical fiber transmission. 2012.

5. R. G. H. Van Uden, R. A.ua Correa, E. A. Lopez, F. M. Huijskens, C. Xia,G. Li, A. Schülzgen, H. de Waardt, A. M. J. Koonen and C. M. Okonkwo, Ultra-high-density spatial division multiplexing with a few-mode multicore fibre. Applied physics, 2014.

6. K. I. Selwan, Study of multilevel modulation formats for high speed digital optical communication systems. Department of Electrical Engineering and Mathematics, Paderborn, Germany, 2007.

7. F. Idachaba, D. U. Ike and O. Hope, Future Trends in Fiber Optics Communication. Proceedings of the World Congress on Engineering. London, U.K. 2014.

8. Fujitsu network communication white paper, Beyond 100G, 2013.

9. ITU, Spectral grids for WDM applications: DWDM frequency grid, ITU. G.694. 2012.

10. K. Szczerba, J. Karout, J. S. Gustavsson, Å. Haglund, M. Karlsson, P. A. Andrekson, E. Agrell and A. Larsson, 4-PAM for High-Speed Short-Range Optical Communications. OPT. comm.network, 2012. Vol. 4**.** (No. 11).

11. L. Tao, Y. Ji, J. Liu, A. P.Tao Lau, N. Chi and C. Lu, Advanced modulation formats for short reach optical communication systems. IEEE, 2013.

12. X. Xu, E. Zhou, G. N. Liu, T. Zuo, Q. Zhong, L. Zhang, Y. Bao, X. Zhang, J. Li and Z. Li, Advanced modulation formats for 400 Gbps short-reach optical inter-connection. Optics ecpress. 2015. Vol. 23**.**(No.1).

13. Infinera. What comes after 100G? DWDM Super-channels, white paper Infinera. 2012. [cited 22 september 2015].

14. K. Murata and T. Saida, Optical Device Technologies for Future Network Evolution. NTT Technical review. 2011. Vol. 9**.**(No.3).

15. N. Massa, Fundamentals of Photonics: Fiber optic telecommunication. University of Connecticut.2000.

16. H. J. R. Dutton, Understanding optical communications. IBM cooperation International Technical Support Organization.1998.

17. S. Makovejs, High speed optical fibre transmission using advanced modulation formats. Department of Electronic and Electrical Engineering. University College of London. London.2011.

18. J. Hecht, Understanding fiber optics. Prentice hall.1999.

19. T. B. Gibbon, K. Prince, C. Neumeyr, E. Rönneberg, M. Ortsiefer and I. T. Monroy, VCSEL transmission at 10 Gb/s for 20 km single mode fibre WDM-PON without dispersion compensation or injection locking. Elsevier. Opt. Fib. technology. 2011. Vol**. 17.** pg: 41-45.

20. S. Elahmadi, M. D. Srinath and D. Rajan, Channel capacity and modeling of optical fiber communications. IEEE. 2009.

21. J. D. Downie, M. Sauer and J. Hurley, Flexible 10.7 Gb/s DWDM transmission over up to 1200 km without optical in-line or post-compensation of dispersion using MLSE-EDC. OSA. 2010.

22. J. Leuthold, Optical Communications Systems - Part 2: Transmitters and modulation formats. Institute of Photonics and Quantum Electronics (IPQ). 2011.

23. G. P. Agrawal, Fiber-optic communication systems. Fourth edition. ed. John Wiley and Sons.2007.

24. X. Li, R. Mardling and J. Armstrong, Channel Capacity of IM/DD optical communication systems and of ACO-OFDM. IEEE. 2007.

25. D. G. Messerschmitt, How digital communication works.University of California.1999.

26. G. Keiser, Optical fibre communications. 3rd Ed. McGraw Hill.2000.

27. R. S. Vodhanel, A. F. Elrefaie, M. Z. Iqbal, R. E. Wagner, J. L. Gimlett and S. Tusuji, Performance of directly modulated DFB lasers in 10-Gb/s ASK, FSK and DPSK. Lightwave Systems. Journal of Lightwave Technology. 1990. Vol. 8.(N0.9). pp: 1379.

28. J. B. Jensen, M. I.Olmeido and I. T. Monroy, Modulation formats for beyond-100Gbps Ethernet Optical Links – A Review of Research. OSA. 2013.

29. E. Lach and W. Idler, Modulation formats for 100G and beyond. Optical Fiber Technology. 2011. Vol. 17**.** pp: 377–386.

30. P. J. Winzer and R.J. Essiambre. Advanced Optical Modulation Formats. IEEE. 2006.

31. T. Yamamoto, High speed directly modulated lasers. Technical presentation: Fujitsu Laboratories Ltd. 2010.

32. P. Krehlik, Characterization of semiconductor laser frequency chirp based on signal distortion in dispersive optical fiber. Opto-Electronics Review. 2006.

33. M. F.L. Abdullahand R. Talib, Multilevel signal analyzer tool for optical communication system. International Journal of Electrical and Computer Engineering (IJECE). 2012. Vol. 2**.**(No. 4.): pp: 529-536.

34. C. Peucheret, Generation and detection of optical modulation formats.Department of Photonics Engineering. Technical University of Denmark.2012.

35. H. Muhammad, Advanced modulation formats for high bit rate optical networks.School of electrical and computer engineering. Georgia Institute of Technology. Georgia.2008.

36. F. Karinou, R. Rodes, K. Prince, I. Roudas and I. T. Monroy, IM/DD vs 4-PAM Using a 1550 nm VCSEL over short range SMF/MMF links for optical interconnects. OFC/NFOEC Technical Digest OSA. 2013. pp. 4.

37. M. O. Al-Dwairi, Evaluation of multilevel modulation formats for 100Gbps transmission with direct detection. Journal of Electrical, Computer, Electronics and Communication Engineering. 2013. Vol: 7.(No. 8).

38. G. A. Mahdiraji and A. F. Abas, Advanced modulation formats and multiplexing techniques for optical telecommunication systems.Trends in telecommunications technologies. 2010.

39. Cooperation. I. 40 G QPSK and DQPSK modulation. 2011.

40. H.Signh, Performance analysis of different modulation formats in dispersive optical communication system. Thapar University.2008.

41. S.K. Mohapatra, R. Bhojray and S.K. Mandal, Analogue and digital modulation formats of optical fiber communication within and beyond 100 Gb/s: A comparative overview. (IJECET). 2013. Vol. 4.(No. 2. ): pp: 198-216.

42. S. K. Mohapatra, R. R. Choudhury, R. Bhojray and P. Das, Performance analysis and monitoring of various advanced digital modulation and multiplexing techniques of fibre optic communication within and beyond 400 Gb/s. International Journal of Computer Networks & Communications (IJCNC). 2014. Vol. 6.(No. 2).

43. R. Chhilar, J. Khurana and S. Gandhi, Modulation formats in optical communication system. International Journal of Computational Engineering and Management (IJCEM). 2011. Vol. 13.

44. N. Kikuchi and R. Hirai, Intensity-Modulated/Direct-Detection (IM/DD) Nyquist pulse-amplitude modulation(PAM) signaling for 100-Gbit/s optical short-reach transmission. (Ecoc).Cannes France.2014.

45. J. J. Bevensee, R. l. Rodes, I. T. Monroy and C. Jambrinao, 1.3 μm all-VCSEL low complexity coherent detection scheme for high bit rate and high splitting ratio PONs. Optical fiber communication conference and exposition (OFC/NFOEC) and the National fiber optic engineers conference. Optical Society of America. San Francisco.2011.

46. S. Jawla and R. K. Singh, Phase shift modulation formats in optical communication system. International Journal of Advancements in Research and Technology. 2013. Vol. 2.(No. 11.) pp: 72.

47. V. K. Ingle and J. G. Proakis, Digital signal processing using MATLAB. Third Ed. 1997.

48. J. J. Bevensee, R. l. Rodes and I. T.Tafur Monroy, Coherent detection for 1550 nm 5 Gbit/s VCSEL based 40 km bidirectional PON transmission. Proc. in Optical fiber communication conference and exposition (OFC/NFOEC) and the National fiber optic engineers conference. Optical society of America. 2011.

49. R. L. Rodes, Vertical-Cavity Surface-Emitting Lasers:Advanced modulation formats and coherent detection, Department of Photonics Engineering Building 3432013. Technical University of Denmark: Lyngby DENMARK. 2012.

50. A. M. Joshi, S. Datta and A. Crawford, Next-Geneneration communications fiber: Multilevel modulation formats push capacities beyond 100 Gbit/s. Laser focus. 2012.

51. T.Y.Elganimi, Performance comparison between OOK, PPM and PAM modulation schemes for free space optical (FSO) communication systems: Analytical Study. International Journal of Computer Applications. 2013. Vol. 79.(No. 1).

52. P. Ramantanis, Contribution to the analysis of optical transmission systems using QPSK modulation. TELECOM and Management SudParis and Université Pierre et Marie Curie - Paris.2012.

53. J. Leibrich, C. Wree and W. Rosenkranz, Phase-Shift-Keying (PSK & DPSK) techniques for long haul Wavelength division multiplexing systems over standard single mode fiber. University of Kiel, Germany.2010.

54. C. Jambrina, A. Ezra, A. P. Tao Lau, D. J. F. Barros and J. M. Kahn, Coherent detection in optical fiber systems. Optical Society of America. 2008. Vol.16**.** (No. 2.)pp. 753.

55. A. Gorshtein and D. Sadot, Advanced modulation formats and digital signal processing for fiber optic communication. Proc. in International conference on Transparent Optical Networks (ICTON). Munich, Germany.2010.

56. D. S. Ly-Gagnon, S. Tsukamoto, K. Katoh and K. Kikuchi, Coherent detection of optical quadrature phase- shift keying signals with carrier phase estimation. Journal of lightwave technology. 2006. Vol. 24.(No. 1).

57. A. Macho, Digital coherent receivers and advanced optical modulation formats in 100 and 200 Gb/s DWDM systems. Proc in IEEE Escuela Técnica Superior de Ingenieros de Telecomunicación Universidad.2014.

58. Optical hybrid enables next-generation optical communication. 2012 [cited 20 July 2015].

59. J. Leibrich, C. Wree and W. Rosenkranz, Phase-Shift-Keying (PSK & DPSK) techniques for long haul wavelength division-multiplexing systems over standard single mode fiber. University of Kiel.2000.

60. T. V. Chabata, E. K. Rotich Kipnoo, R. R. G. Gamatham, A .W. R. Leitch and T. B. Gibbon,A single DFB laser for multilevel directly modulated signal for high speed optical fibre communication system. in Proc. 59th Annual Conference of the South African institute of physics (SAIP). University of Johannesburg.2014.

61. M. Karim, G. Wang and R. Wong, Quadrature amplitude modulation with 16 M-ary number over intersymbol interference channel. 2010.

62. K. Kikuchi and S. Kawakami, Multi-level signaling in the Stokes space and its application to large-capacity optical communications. Optical Society of America. 2013. Vol. 22.(No. 7).

63. R. L. Rodes, N. J. Jensen and I. T. Monroy, 10 Gb/s Real-Time All-VCSEL low complexity coherent scheme for PONs. in Proc, Optical Fiber Communication Conference. Optical Society of America.Los Angeles, California. 2012.

64. T.V. Chabata, E. Rotich, R. R. G. Gamatham, A. W. R. Leitch and T.B. Gibbon,A higher order modulation format for 20 Gbps in a high capacity optical communication system. in Proc. 7th African Laser Centre (ALC) Annual Workshop and 3rd Moroccan Days on Nanoscience and Nanotechnology (MDNN3). MAScIR, FSR –UM5, Rabata–Morocco. 2014.

65. H. M. Fisher and F. R. Arams, Photodetectors for optical communication systems. IEEE. 1970. Vol. 58.(No. 10).

66. R. E. Kirwa, Fibre optic network supporting high speed transmission in the Square Kilometre Array, South Afrca. Centre for Broadband Communication. Nelson Mandela Metropolitan University.2014.

67. Agrawal, G.P, Fiber-Optic Communications Systems. 2002. John Wiley & Sons, Inc.

68. S. Jawla and R. K. Singh, Different modulation formats used in optical communication system. International Journal of Advancements in Research and Technology. 2013.Vol. 8. (No. 4). pp: 15-18.

69. K. Achyut, M. Dutta and I. Saif, Novel broadband photodetector for optical communication. in Proc, SPIE. Santa Clara.2005.

70. J. C. Rasmussena, T. Tanimuraa, H. Nakashimaa, S. Odaa, Z. Taob and L. Lib, Advances in coherent detection algorithms. 2011.

71. Y. Inada, Recent advances and trends for digital coherent 100Gb/s and beyond technologies in submarine optical cable. 2010.

72. F. Patarnello, Sampling digital coherent receiver for demultiplexing and processing of OTDM signals employing high-order modulation. Danmarks Tekniske Universitet - Fotonik.2010.

73. P. Salehi, Fundamentals of Communications Systems. Pearson Prentice Hall.2005.

74. Optoplex coorperation, white paper, Optical hybrid enables next generation optical communication. 2012.

75. D. Zhang, Digital signal processing of POL-QAM and SP-QAM in long haul optical transmission systems., in Electrical and Computing Engineering.Concorda University.2014.

76. K. D. B. Zid and K. R. P. Zid. Linear distortion management in optical fibers using dispersioncompensatingfiber. Available from: https://sites.google.com/site/dcspprojectcognizats/impairments-in-optical-fiber-transmission. 2013.

77. Cisco, Fiber types in Gigabit Optical Communications, Transceiver Modules.Technical paper. 2008.

78. M. Mussolin, Digital signal processing algorithms for high-speed coherent transmission in optical fibers. in Proc Facola di Ingegneria. Universita degli studi di Padova. Italy.2010.

79. X. Li, X. Chen, G. Goldfarb, E. Mateo, I. Kim, F. Yaman and G. Li, Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing. Optical Society of America. 2008. Vol.16.(No. 2.).

80. M. Arumugam, Optical fiber communication- An overview. Pramana Journal of Physics., 2001. Vol. 57.(No. 5 and 6.). pp:849–869.

81. N. K. Kahlon and G. Kaur, Various dispersion compensation techniques for optical system: A Survey. Open Journal of communications and software. 2014. Vol. 1(No. 1).

82. C.Y. Lin, M. Rameez Asif, M. Holtmannspoetter and B. Schmauss, Evaluation of nonlinear phase noise in DQSK transmission for different link designs. Physics Procedings. 2010. Vol. 5.

83. G. K. S. Devra, Different compensation techniques to compensate chromatic dispersion in fiber optics. International Journal of Engineering and Information Technology. 2011. Vol. 3**.**(No.1). pp: 1–4.

84. G. Li, Recent advances in coherent optical communication. OSA. 2009. Vol. 1**.** pp: 279–307.

85. A. Kaur, Polarization mode dispersion compensation in WDM system using dispersion compensating fibre. International Journal of Engineering Research and Applications (IJERA). 2012. Vol. 2.(Issue 2.): pp: 668-673.

86. M. Kuhn, Digital signal processing. University of Cambridge.2009.

87. X. Zhang, Digital Signal Processing for Optical Coherent Communication Systems. Department of Photonics Engineering. Technical University of Denmark. DTU Fotonik. Denmark.2012.

88. A. P. T. Lau, Y. Gao, Q. Sui, D. Wang, Q. Zhuge, M. H. Morsy-Osman, M. Chagnon, X. Xu, C. Lu and D. V. Plant, Advanced DSP techniques enabling high spectral efficiency and flexible transmissions. IEEE signal processing magazine. 2014.

89. S. P. Singh and N. Singh, Nonlinear effects in optical fibers: Origin, management and applications. Progress in Electromagnetics Research, PIER. 2007. Vol. 73. pp: 249–275.

90. Fibre Optic Association, Fiber characterization and testing long haul, high speed fiber optic networks. 2010.

91. I. Roudas, Coherent optical communication systems in WDM systems and networks, optical networks. Springer science.2012.

92. J. Sitch, High-speed digital signal processing for optical communications. in Proc, European conference on Optical communication (ECOC). Brussels, Belgium.2008.

93. R.N. Mutagi, Pseudo noise sequences tor engineers. Electronics and communication engineering Journal. 2006.

94. M. G. Taylor, Algorithms for coherent detection. OSA / OFC/NFOEC. 2010.

95. T. V. Chabata, R. R. G. Gamatham, H. Y. S. Kourouma, E. K. Rotich Kipnoo, A. W. R. Leitch and T.B. Gibbon, Digital signal processing algorithm for signal reconstruction and performance measurement for a single photo-detector optical communication system. in Proc.16th annual Southern Africa Telecommunication Networks and Applications Conference (SATNAC). Spiers, Stellenbosch, Western Cape, South Africa 1-4th Sept 2013.

96. S.Zhang, Advanced optical modulation formats in high-speed lightwave system. Electrical Engineering and Computer Science. University of Kansas. 2011. pp: 90.

97. E. Ciaramella, A. Peracchi, L. Banchi, R. Corsini and G. Prat, BER Estimation for Performance Monitoring in High-Speed Digital Optical Signals. Journal of Lightwave Technology. 2012. Vol. 30.( No.13).

98. D. Corish, Eye patterns' and error rate analysis in optical communications. DIT School of Physics.2005.

99. Anristu, Understanding eye pattern measurements. Application note. 2010.

100. I. Ali, Bit-Error-Rate (BER) simulation using MATLAB. International Journal of Engineering Research and Applications (IJERA). 2013. Vol. 3.(No. 1.). pp: 706-711.

101. H. W. Lin, Wide-bandwidth interface circuit design basic optical communication concept (3) BER / Q / SNR. YuanZe University.2013.

102. Anristu, Understanding eye pattern measurements. Application note. 2012.

103. I. Rasheed, M. F. A. Sial, K. S. Ali and T. Mehboob, Evaluation of optical receiver sensitivity. Bit Error Rate (BER) / Q-factor. International Conference on Computer and Communication Technologies. 2012. Vol. 30**.** (NO. 13).

104. K. Buchs, P. Zabinski and J. Coker, Basic bit error rate analysis for serial data links. Rochester. Mayo Clinic.2004.

105. K. Cho and D. Yoon, On the general BER expression of one and two-dimensional amplitude modulations. IEEE. 2002.

106. Radio Electronics.com. Bit error rate tutorial and definition.2013.[cited http://www.radio-electronics.com/info/rf-technology-design/ber/bit-error-rate-tutorial-definition.php. Accessed 26 June,2015].

107. B. Linlin, L. Jianming, L. Li and Z. Xuecheng, Comprehensive assessment of new modulation techniques in 40Gb/s optical communication systems.3rd International Photonics and Opto-Electronics Meetings. China.2011.

108. L. Zhixin, Design and applications of advanced optical modulation formats for optical metro/Access transmission systems. in Proc. Information Engineering.The Chinese University of Hong Kong.2012.

109. R. Udayakumar, V. Khanaa and K. P. Kaliyamurthie,High data rate for coherent optical wired communication using DSP. Indian Journal of science and technology. 2013. Vol. 6**.**

110. J. E. Gilley, Bit-error-rate simulation using Matlab. I. Transcrypt international, editor 2003.

111. R. E. Frey, Lecture Notes for Digital Electronics. University of Oregon.2000.

112. A. Irfan, Bit error rate (BER) simulation using MATLAB. International Journal of Engineering Research and Applications. 2013. Vol. 3.(No. 1.). pp: 706 -711.

113. S. Shi, J. Yan, L. An and Z. Zheng, Performance analysis of an all-optical regenerator for DQPSK/QPSK based on phase-sensitive amplifiers. in Proc. of SPIE. 2008.

114. L. D. Coelho, Modeling, Simulation and Optimization of optical communication systems using advanced modulation formats. Teschnische Universit at Mucnchen.2010.

115. R. Ali, M. S. Ali,T. Mir, B. Shabir and U. F. Lilla , Analytical review of advanced optical modulation formats. Electrical and Electronics Engineering. 2015. Vol. 4.(No. 1).

116. S. Gupta and G. Wassson, Performance of BER for BPSK and DPSK (coherent and non-coherent) modulation in Turbo-Coded OFDM with channel equalization. International Journal of Soft Computing and Engineering (IJSCE). 2013. Vol.3.(No. 1). pp: 2231-2307.

117. D. S. Millar, Digital signal processing for coherent optical fibre communications. Department of Electronic and Electrical Engineering. University College London.2012.

118. R. L. Rodes, Vertical-Cavity Surface-Emitting Lasers:Advanced modulation formats and coherent detection. Photonics Engineering.Technical University of Denmark. Denmark.2013.

119. M. Poulin, C. Latrasse, J.F. Gagné, Y. Painchaud, M. Cyr, C. Paquet, M. Morsy-Osman, M. Chagnon, S. Lessard and D.V. Plant,107 Gb/s PAM-4 Transmission over 10 km using a SiP Series Push-Pull Modulator at 1310 nm . ECOC. 2014.

120. V. K. Ingle and J. G. Proakis, Digital signal processing using MATLAB. Global Engineering. USA. 2012.

121. M.Chagnon, M. Osman, M. Poulin, C. Latrasse, J. F. Gagné, Y. Painchaud, C. l. Paquet, S. Lessard and D. Plant, Experimental study of 112 Gb/s short reach transmission employing PAM formats and SiP intensity modulator at 1.3 μm. Optics express. 2014. Vol. 22.(No.17).