Design and Performance Analysis of WDM PON Based on Heterodyne Receiver for 5G Transport Network

Aschalew Girma Lame

A Thesis Submitted to Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of

Master's in Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

June 2024

Adama, Ethiopia

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Co Advisor Dr. Ram Sewak Singh

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APPROVAL PAGE OF M.SC THESIS

We, the advisors of the thesis entitled "**Design and Performance Analysis of WDM PON Based on Heterodyne Receiver for 5G Transport Network**" developed by **Aschalew Girma Lame**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by **Aschalew Girma Lame** have read and evaluated the thesis "**Design and Performance Analysis of WDM PON Based on Heterodyne Receiver for 5G Transport Network**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication Engineering.

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DECLARATION

I declare that this Master Thesis entitled "**Design and Performance Analysis of WDM PON Based on Heterodyne Receiver for 5G transport Network**" is my own work and has not been submitted to any university for similar purpose. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been fully acknowledged through citation.

Aschalew Girma

Name of student	Signature	Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "**Design and Performance Analysis of WDM PON Based on Heterodyne Receiver for 5G Transport Network**" prepared under our guidance by **Aschalew Girma Lame** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electronics and Communication Engineering. Therefore, we recommend the submission of a revised version of the thesis to the department following the applicable procedures.

Dr. Demissie Jobir	________________	________________
Major Advisor	Signature	Date
Dr. Ram Sewak Singh	________________	________________
Co-advisor	Signature	Date

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATION

ASK	Amplitude Shift Keying
BBU	Baseband Unit
BER	Bit Error Rate
C-RANs	Cloud-Radio Access Networks
mMTC	massive machine type communication
eMBB	enhanced mobile broadband
URLLC	Ultra Reliable Low Latency Communication
CU	Central Unit
DBA	Dynamic Bandwidth Allocation
DP-QPSK	Dual-polarization Quadrature Phase-shift keying
DSP	Digital Signal processing
DU	Distributed Unit
FH	Fronthaul
FSK	Frequency Shift keying
IEEE	Institute of Electrical and Electronics Engineers
LO	Local Oscillator
LTE	Long Term Evolution
NG-EPON	Next Generation Ethernet Passive Optical Network
ODN	Optical Distribution Network
OLT	Optical Line Terminal,
ONU	Optical Network Unit
OTN	Optical Transport Network
OSNR	Optical Signal to Noise Ratio
PAM	Pulse Amplitude Modulation
PSK	Phase Shift Keying
P2P	Point-to-point
RU	Remote Unit
EVM	error vector magnitude
TDM-PON	Time Division multiplexing Passive Optical Network

TWDM	Time and Wave Division multiplexing
WDM	Wavelength division multiplexing
4G	Fourth generation mobile network
5G	Fifth generation mobile network
SER	Symbol Error Rate
EFH	Ethernet fronthaul
EoF	Ethernet Over Fiber
LED	Light Emitting Diode
LD	Laser Diode
PIN	Positive Intrinsic Negative
APD	Avalanche Photo Diode
IF	Intermediate Frequency
PLL	Phase Locked Loop
RoF	Radio Over Fiber
DAS	Distributed Antenna System
OAN	Optical Access Network
CWDM	Coarse Wave Length Division Multiplexing
DWDM	Dense Wave Length Division Multiplexing
CW	Continuous Wave
BPF	Band Pass Filter
PBC	Polarization Beam Combiner
PBS	Polarization Beam splitter
XPM	Cross Phase Modulation
FWM	Four Wave Mixing
SPM	Self-Phase Modulation
PMD	Polarization Mode Dispersion
DGD	Differential Group Delay

ABSTRACT

The development of fifth generation (5G) wireless networks is aimed at satisfying the growing need for fast data transmission. An optical network with high speed and reliability is needed to facilitate 5G transport. Passive optical networks (PONs) are becoming a viable option for 5G transport because of their scalability and affordability. Wavelength Division Multiplexing Passive Optical Networks (WDM-PONs) have attracted a lot of interest because of its capacity to provide a wide range of services to numerous customer. In this thesis, the performance of WDM -PON based on a heterodyne receiver for 5G transport has been evaluated. The result of simulation suggested that under different modulation the WDM PON is capable of providing 5G transport with high data rates, and good spectrum efficiency. The system selectivity and sensitivity is enhanced by heterodyne receiver by reducing the noise and distortion. The right optical components and wavelengths for data transmission are chosen as part of the system's design and performance study. Effective performance measurement like bit error rate (BER) symbol error rate (SER), error vector magnitude (EVM), quality factor and constellation diagram are used to assess the system performance. From the result analysis, it is observed that average Q-factor is 21.12 at 100 Gbps and 100km, which shows that the goodness of system performance, the average BER value is 0.000103312, at 100km and 100 Gbps, the average SER of 0.000153055 is achieved at 100km and 100Gbps, the average EVM of 5.124994 is achieved at 100Gbps and 100km fiber length and the less noisy constellation point arrangement is found at 100Gbps and 100 km fiber length. As the data rate and fiber length increase the quality factor is decrease and BER, SER, EVM % is increase. The above achieved value is evaluated under QPSK modulation which have large constellation space between the symbol and less prone to error.

***Keywords:* Passive Optical Network (PON), BER, Wavelength Division Multiplexing (WDM), Heterodyne receiver**

CHAPTER ONE
INTRODUCTION

1.1 Background of the Study

The widespread usage of mobile devices and the introduction of new applications have resulted in a tremendous increase in data traffic, placing unprecedented demands on the communication infrastructure. The emerging of new application such as internet of things (IoT), autonomous vehicles and smart cities need for higher bandwidth, lower latency and strong signal quality. The main objective of 5G services is to support three generic services: enhanced mobile broadband (eMBB) which is 5G service category that focus on speed, capacity and mobility of 5G. massive machine type communications (mMTC) means connecting large numbers of devices in a given area and ultra-reliable low-latency communications (URLLC) that enables high-reliability and low-latency communication. The access of eMBB, mMTC and URLLC using PON service and point to point service is shown in figure 1.1. In order to satisfy these demands, optical and wireless networks work in concert to provide a more seamless experience for both fixed and mobile applications than either could provide on its own. The revolutionary objectives of 5G would not be feasible without fiber (Terada, 2019).

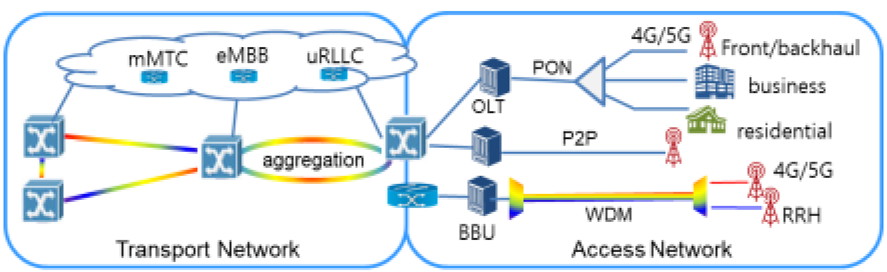


Figure 1.1 5G transport and access networks architecture(Terada, 2019).

In addition to having a faster speed and more bandwidth than 4G/LTE, 5G networks are made to support communications between massive machines and the cloud and virtualized networks. Cloud-radio access networks (C-RANs) have recently been introduced as a key concept to address the shortcomings of conventional RAN systems and support services that require incredibly low latency, high reliability, density, and mobility. In CRAN, the Baseband Unit (BBU) pool is located in the Central Unit (CU), which is linked to the Remote Units (RUs) by high-bandwidth transport links that transmit I/Q streams, or fronthaul (FH). Typically, the Distributed Unit (DU) is deployed outside, while the Central Unit (CU) is installed in the central office. In the current optical distributed network (ODN), optical fiber is used to connect the Fronthaul physical link.

Plenty of technologies such as point-to-point fiber access, passive optical network (PON), Flexible Ethernet, and optical transport network (OTN) are alternating solution to be proposed for 5G transport system. P2P fiber access is the most straight forward technique and has been widely deployed in fiber-rich area. P2P fiber access is likely to form the foundation for the majority of 5G transport for immediate deployment. In the long run, P2P access, however, could not be viable outside of locations with plenty of fiber and it is not cost effective for new implementation. PON is a point-to-multipoint system with the advantage of high fiber efficiency. The components of a typical PON system are an optical line terminal (OLT) which is found the central office, and optical distribution network ODN) with passive power or wavelength splitters, and optical network units (ONUs) at the locations of the subscribers(Wey et al., 2018).Using passive optical network (PON) architecture, several base stations (BS) can share equipment and infrastructure, which is becoming a more affordable option. The interconnection of OLT with ONU using single mode optical fiber is shown in figure 1.2. One of the key challenges in fronthaul links to deliver massive connectivity, low latency, and capacity enhancement in 5G wireless systems is the support of guaranteed bandwidth and low latency with cost-effective optical technologies (Wey et al., 2020). The upcoming 5G technology promises to address this need in order to provide high-speed services to end users in a cost and energy-efficient manner, passive optical network (PON) technologies that use wavelength division multiplexing (WDM) is proposed. By enabling effective use of the optical spectrum and minimizing the delay and cost associated with the use of separate optical fiber for each user, WDM PON architecture is a crucial way to meet the bandwidth requirements of 5G transport. the performance of WDM PON functions is mainly dependent on the receiver's design, the receiver is taking the generated optical signal and translating it into an electrical signal with high sensitivity and low noise. Thus, this study aims to develop, assess, and contrast the capabilities of a heterodyne-based WDM PON for 5G transmission. The study's findings will be useful in determining the best ways to develop and optimize WDM PONs for next-generation communication networks.

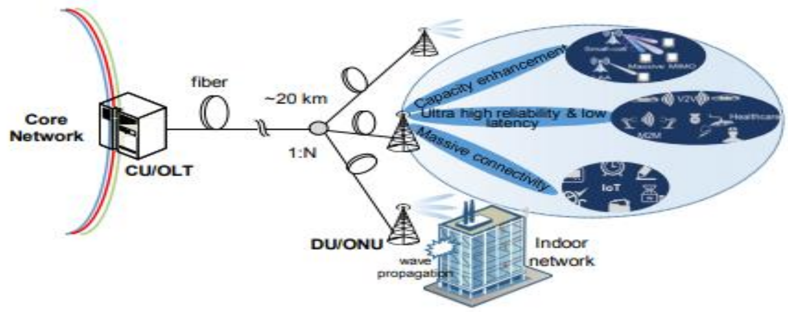


Figure 1.2 Optical access network for 5G mobile communication networks (Chung, 2018).

The ODN uses a passive optical power splitter for TDM-PON. All ONU signals are multiplexed in the time domain, and each ONU burst broadcasts in the upstream direction at a specific time-slot. In WDM-PON, specific wave length is assigned for each ONU (Jacob & Raj, 2015). When it comes to wavelength selectivity via wavelength filters, the ONU or the ODN can both use passive wavelength splitters. The fronthaul interface requirements for delay-sensitive 5G applications are incompatible with TDM-PON's use of the conventional dynamic bandwidth allocation (DBA) mechanism, which might cause delays of up to one millisecond(Chung, 2018). On the other hand, the most effective PON that can accommodate more users is wavelength division multiplex. We anticipate that WDM PON will be a major player in the optical communication network because of its capacity to provide higher downstream and upstream rates, competitive price, and more bandwidth. The success of 5G is largely due to the optical access networks made possible by Passive Optical Networks (PON), because of their point-to-multipoint structure, fiber resources may be used efficiently(Wen & Lee, 2022).

A technique known as Wavelength Division Multiplexing Passive Optical Network (WDM-PON) combines the benefits of passive optical network (PON) and wavelength division multiplexing (WDM) designs. Data is transmitted between the optical line terminal (OLT) and the optical network units (ONUs) or optical network terminals (ONTs) using a variety of light wavelengths in WDM PON and wavelength can carry a distinct signal which enables high-speed data transmission (Wen & Lee, 2022). TDM is used to assign time slots for data transmission between the OLT and ONUs/ONTs, as a result, multiple users can effectively share the available bandwidth. As the demand for high-speed data service rise tremendously in modern network, the shared bandwidth become hitch for implementation of 5G. This restriction is overcome by WDM-PON, which uses several wavelengths, or colors of light, to transmit data concurrently over a single optical cable.

WDM PON effectively distribute the available bandwidth among multi users and can also increase bandwidth utilization and meet the needs of various users. WDM PON enhance lower latency and high speed, which is applicable for many applications, including 5G transport networks.

1.2 Statement of Problem

The increasing demand for high-speed, high-bandwidth, and low-latency connectivity for 5G transport has led to the need for advanced optical communication systems. The standards for 5G include a peak data rate of 20 Gb/s per sector, a user-experienced data rate of 1 Gb/s, and a latency of 1 ms. In densely populated areas, when the number of users connected to a single sector exceeds 200, and each user's peak data rate may reach 1Gbps, the total aggregate data rate of users could hit 200Gbps. To accommodate users with peak data rates, an additional sector is necessary, and PON is utilized to handle the data rates needed to construct various cells.

However, current systems face challenges such as coverage limitation and high operational cost due to point to point fiber distribution. Therefore, there is a need to develop a new system that provide the use of existing resource of PON of point to multi point to offer high-speed, high-bandwidth, and low-latency connectivity for 5G wireless networks. Therefore, the problem addressed by this thesis is handled by design and analyze WDM PON based on a heterodyne receiver for 5G transport.

1.3 Objectives of the Study

1.3.1. General objective

The general objective of this thesis is to design a WDM based PON transmission system with heterodyne receivers which can satisfy 5G Transport requirements.

1.3.2. Specific objectives

- ✓ To design the topology of WDM based PON transmission system with heterodyne receivers using OptiSystem version 20 software.
- ✓ Compare WDM PON using different modulation techniques, bit rates and fiber length.
- ✓ To assess the systems performance using performance measurements such as bit error rate(BER), symbol error rate(SER), Q-factor, error vector magnitude(EVM) and constellation diagram.

- ✓ To measure the power spectral density of WDM-PON for various modulation techniques.

1.4 Significance of the Study

The proposed architecture can be implemented using existing point to multi point fiber infrastructure and does not require significant additional investment in new fiber deployment. This makes it a cost-effective solution for 5G transport networks. The deployment of 5G networks requires a high-speed and low-latency transport network to connect the radio access network (RAN) to the core network. The proposed WDM PON architecture based on a heterodyne receiver has the potential to meet these requirements and provide a flexible and scalable transport network for 5G. The proposed architecture elaborates benefits of WDM and which allows multiple wavelengths to be transmitted over a single fiber and uses share high bandwidth between users.

1.5 Expected Outcomes of the Study

The performance of modulation technique is analyzed and different fiber length and different bitrate is evaluated using performance metric. From constellation diagram the quality of different modulation scheme is analyzed. BER, SER, EVM, Quality factor and different modulation scheme, mainly QPSK with different fiber length using Heterodyne receiver is analyzed.

1.6 Scope of the Study

The scope of this thesis is mainly about design of WDM with heterodyne receiver for 5G transport system and analyzing of performance using different bit rate and different modulation. In this study the topology of the system is designed by OptiSystem software and the performance is analyzed using parameter such as bit error rate, quality factor, error vector magnitude, symbol error rate and constellation diagram.

1.7 Limitation of the Study

- ✓ The study is limited to the use of OptiSystem software for simulation, which may not provide a completely accurate representation of real-world scenarios.
- ✓ The study assumes ideal conditions for the system components and does not consider the impact of environmental factors such as temperature and humidity on the system's performance.

1.8 Organization of the Thesis

The thesis has been organized into five chapters.

chapter 1 (**Introduction):** this chapter briefly discusses the background of the study, introduction to the research topic, research objectives, significant of the study, a statement of the problem, expected outcome of the study, the scope of the study, and limitation of the study.

chapter 2 (Literature Review): This chapter discuss a review of different literature on 5G transport, passive optical networks, heterodyne receiver, radio over fiber, wave division multiplexing(WDM) and time division multiplexing (TDM).

chapter 3 (Methodology): This chapter briefly discuss on the system model, materials, and methods used to accomplish the research work, simulation parameters used in design, modulation technique by using OptiSystem 20 software.

chapter 4 (Results and Discussion): This chapter mainly focus on discussions and analysis of simulation results obtained with OptiSystem software.

chapter 5 (Conclusion and Future Work): This chapter of the thesis mainly presents a summary of the research findings, a conclusion based on the results, and future recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

PON, which consists of an optical distribution network (ODN), ONU, and OLT, is utilized for FH applications. The ONU is located at the cell sites close to RRH, and the OLT is situated at the operator central office next to BBU. in case of using TDM-PON, OLT can link several ONUs using optical passive splitter; when using WDM-PON, it can do so via a wavelength splitter or array waveguide. TDM-PON offers a number of distinct advantages for FH applications. TDM PON is regarded as an easy-to-use and reasonably priced solution for fiber sharing because it only needs one wavelength. For 5G FH services, the typical TDM-PON latency problem is still a major concern. Thus, researchers have used a number of strategies to reduce the overall delay of DBA (cycle duration), such as differentiating service and coordinated dynamic bandwidth allocation. Differentiating Service: One way to shorten mobile traffic wait times at ONT, as seen in the figure below, would be to offer higher priority, differentiated service to upstream traffic traveling from RU to ONT, as opposed to other traffic using the same PON port at OLT. Fixed bandwidth (BW) or guaranteed bandwidth by DBA could be allocated to provide priority. Fixed bandwidth that assigned for highest priority traffic is shown in figure 2.1. The cons to this strategy is that even in the absence of mobile traffic, the bandwidth is locked and unavailable for use by any other service(Kayum, 2020).

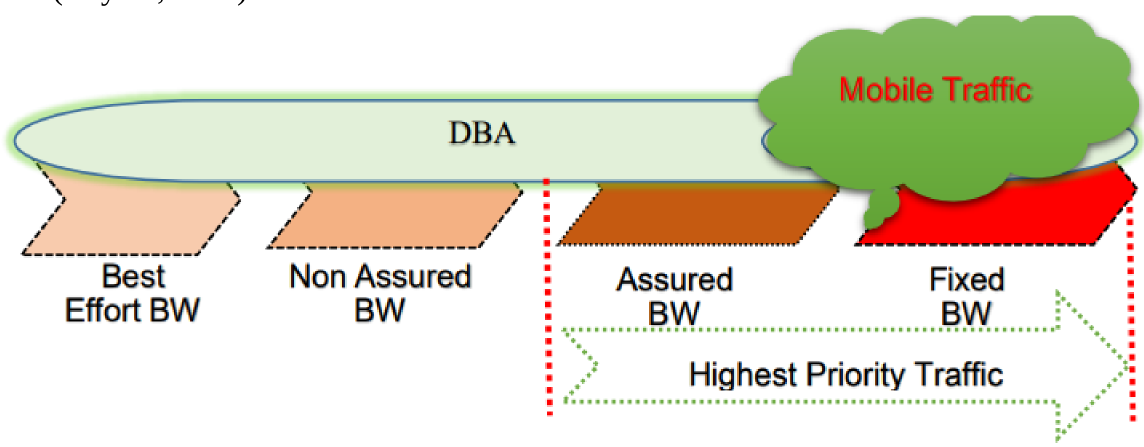


Figure 2.1 Dedicated bandwidth for Low latency 5G fronthaul transport (Kayum, 2020).

Coordinated DBA: another solution reduce wait time of upstream traffic of ONT could be through advance allocation of upstream time slot through exchange of information between OLT and mobile equipment where upstream time slot is allocated as per demand from mobile equipment is shown in figure 2.2.

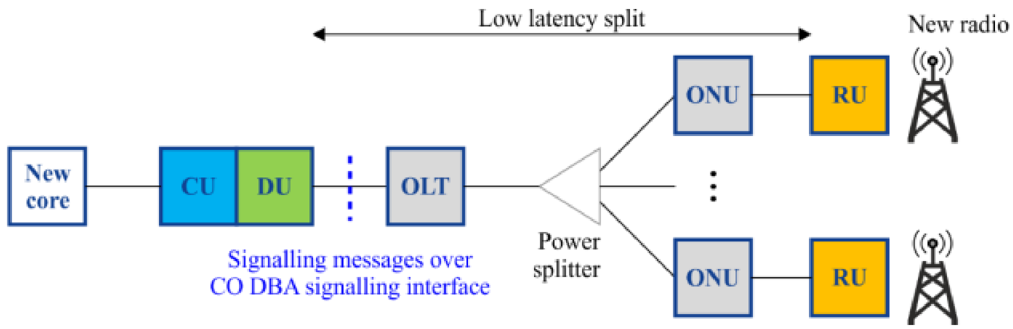


Figure 2.2 Coordinated DBA mechanism for mobile fronthaul (Kayum, 2020).

2.2. System for Optical Communication

Due to the fact that data is transported through glass wires as light waves, optical fiber is a popular choice for transmission channels in communication systems and offers high bit rates over long distances. Three components make up fiber optic communication systems is depicted in figure 2.3.

Figure 2.3 System in optical communication

2.2.1. Optical transmitter

The information-carrying electrical signals are converted to optical signals by an optical transmitter, which then sends the optical signals into an optical fiber. Laser diodes (LDs) and Light Emitting Diodes (LEDs) are mostly used source of light for fiber optic communication.

LEDs are widely employed in fiber optic communication systems due to their compact size, long lifespan, and lower in price and they are utilized in networks with limited bandwidth and small distances.

LDs produce light by amplifying emitted light through simulated emission. Since lasers have a higher output power than LEDs, they are preferable light source for long distance and higher bandwidth communication.

2.2.2. Optical link

An optical fiber is a dielectric waveguide that transports data as light at optical frequencies.

Optical fiber has circular solid core of refractive index(n1) in which light is transmitted through and is surrounded by a cladding having a refractive index n2 (n2 < n1) and the buffer surround the cladding for protection as shown in figure 2.4.

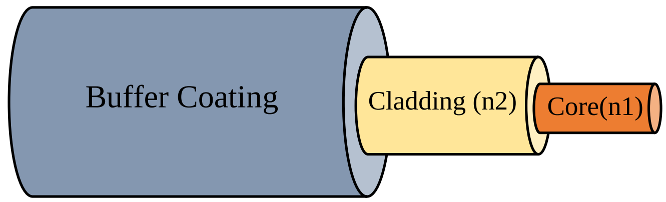


Figure 2.4 Schematic of a conventional silica fibre structure.

2.2.3. Optical receiver

An optical detector which converts the optical signals back to electrical signals so that the information is recovered and delivered to the destination. An ideal optical receiver will have high sensitivity, large bandwidth and low temperature sensitivity, low power consumption and polarization independence.

In fiber optic communication systems, the following optical receivers are most frequently used(Kharraz & Forsyth, 2013):

1. Positive intrinsic-negative (PIN) photodiodes: when thick intrinsic depletion region sandwiched between negative and positive doped regions. Due to its manufacturer simplicity, long durability, less probe to noise, low voltage, and relatively large bandwidth, PINs photodiode are widely used receivers in latest fiber optic communication systems.

2. Avalanche photodiode (APD) receivers: is a type of photodiode that uses an avalanche process for internally amplification of photo current. APD has higher sensitivity because of internal amplification without using external electronic equipment.

Compared to PIN, APD has a higher gain and bandwidth, but it also needs a lot more voltage delivered across the active region.

2.3. Heterodyne Receiver

A heterodyne receiver is a type of optical receiver that uses a local oscillator to convert an incoming signal into baseband or intermediate frequency (IF) for further processing. A heterodyne receiver generally translates a high-frequency signal, like a radio broadcast or a radar signal, to a lower intermediate frequency for the purposes of amplification and demodulation in radio communication.

To create the intermediate frequency(IF) signal, the incoming signal is combined with the signal from the local oscillator. The local oscillator produces a signal at a frequency that is different from the incoming signal. After the IF signal has been amplified and demodulated, the original information signal is retrieved. The received signal is amplified and detected to separate the information stream. It is paired with the reference optical signal produced at a slightly different frequency by the local oscillator. Heterodyne receivers are widely used in coherent optical communication systems when high selectivity and sensitivity are needed. Heterodyne receivers provide several advantages over other types of receivers, such as homodyne receivers or direct conversion receivers. Their high sensitivity and selectivity make them appropriate for applications with low signal-to-noise ratios or interference. Heterodyne receivers can also have high dynamic range, which enables them to process a range of incoming signal levels (Keiser, 2013). The description of synchronous and asynchronous heterodyne receiver is shown in figure 2.5 a and b respectively

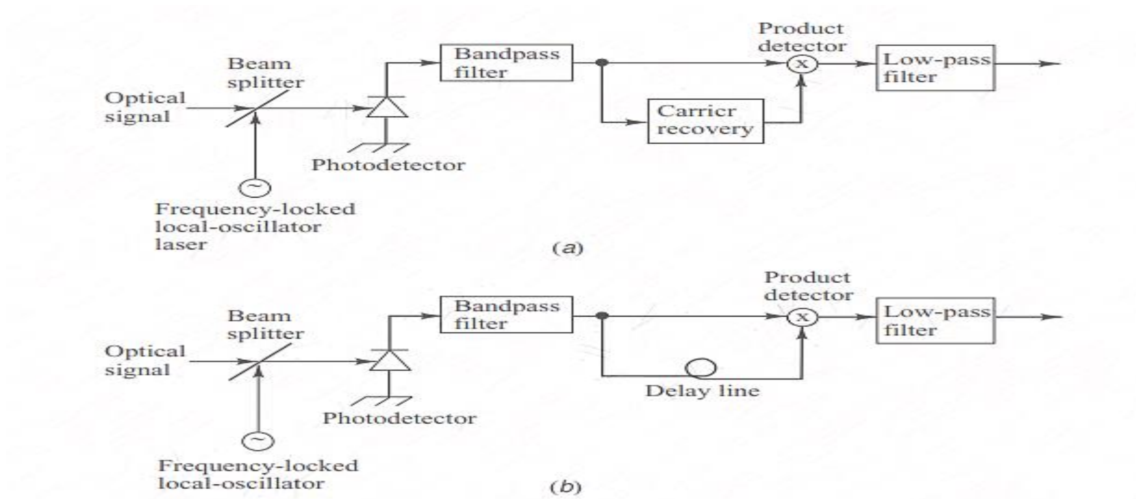


Figure 2.5 General heterodyne receiver configurations. (a) Synchronous detection uses a carrier-recovery circuit. (b) Asynchronous detection uses a one-bit delay line (Keiser, 2013).

Optoelectronic systems frequently use heterodyne receivers to detect and analyze optical signals. There are various important parts and factors to take into account while designing a heterodyne receiver for an optoelectronic system.

1. **Optical components:** selecting the proper optical components is the first stage in creating a heterodyne receiver.
2. **Detector:** In order to convert the optical signal into an electrical signal, the detector is an essential part of a heterodyne receiver. Avalanche photodiodes and PIN photodiodes are among the several kinds of detectors that can be employed. The selection of photo diode detector is based on sensitivity, bandwidth and dynamic range.
3. **Local oscillator:** used to mix a reference local signal with the incoming carrier optical signal. An optical phase-locked loop (PLL), need to make phase alignment. The carrier signal must be phase aligned with modulated signal.
4. **Mixer:** This device combines the local oscillator signal with the incoming optical signal to produce intermediate frequency (IF) signal
5. **Amplification and filtering:** To remove noise and unwanted signals, the IF signal is usually amplified and filtered after produced. Band pass filters isolate frequency in the range of carrier frequency.
6. **Demodulation:** this method is used to retrieve the original information from intermediate frequency. Envelope detection, frequency detection and phase detection is among modulation method used.

2.4. Wavelength Division Multiplexing (WDM)

In fiber optic communication networks, wavelength division multiplexing (WDM) is a technology that enhance the system's bandwidth and capacity. WDM uses several light wavelengths to transport separate signals, allowing numerous optical signals to be delivered simultaneously over a single optical fiber as shown in figure 2.6. WDM combines several light wavelengths onto a single optical fiber. separated optical signal that can be transmitted and received independently of other signals is represented by each wavelength (Rajalakshmi et al., 2011).Transmitted data including audio, video, and data transmitted can be modulated . Coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM) are the two main types of WDM. CWDM is used for short-distance transmissions and uses a greater wavelength spacing, usually 20 nm. By using a smaller wavelength spacing of 0.8 nm, DWDM is used for transmission of signal over long distance

Comparing WDM technology to conventional communication systems reveals a number of advantages. WDM has high bandwidth, faster data rates, and good transmission quality than conventional system. WDM is also not coasty because it uses fewer fibers to transmit several signals instead of the same number. WDM, in general, is a crucial technology in today's fiber optic communication systems that supports the increasing need for bandwidth and capacity in telecommunications networks and allows for high-speed data transmission (Rajalakshmi et al., 2011)(Alnadesh, 2012).

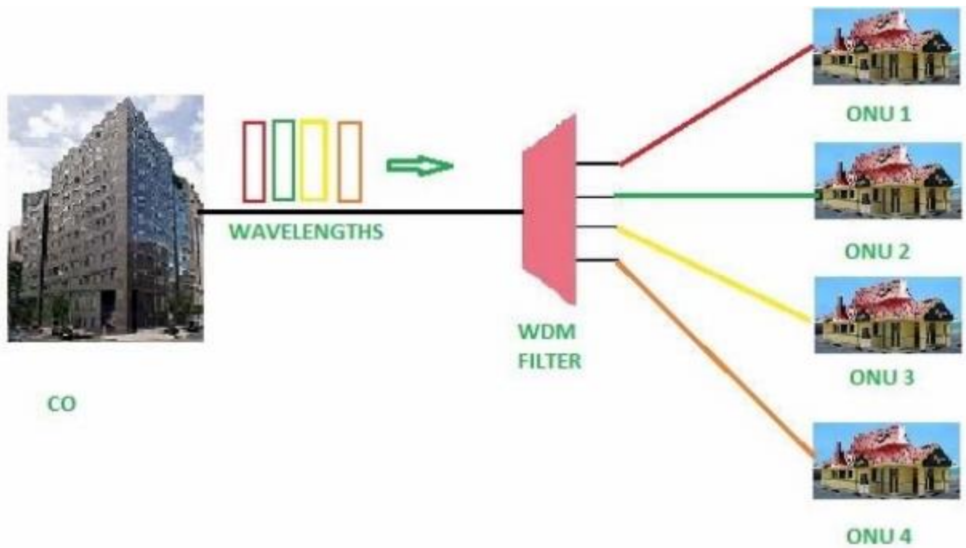


Figure 2.6 Wavelength division multiplexing (Rajalakshmi et al., 2011)

2.5. Time Division Multiplexing (TDM)

In data transmission and telecommunication systems, time division multiplexing (TDM) is a method that allows the transmission of many signals over a single communication channel. TDM divides a single communication channel into multiple time slots, each of which is assigned to a different signal or user as shown in figure 2.7. The repetitive arrangement of the time slots is called a frame. A finite number of time slots, each able to hold a finite quantity of data, are present in each frame. Speech and data signals in digital communication systems, such telephone networks, are commonly carried using TDM. In LANs (Local Area Networks), it also serves to allow several users to share a single communication channel. TDM maximize the usage of communication channel by permitting several signals to share the same bandwidth. By enabling the transmission of numerous signals over a single channel and eliminates the need for extra communication lines. In general, TDM is an important technology in modern communication systems in which several signals or users can share single communication channel and facilitates bandwidth utilization (Rajalakshmi et al., 2011).

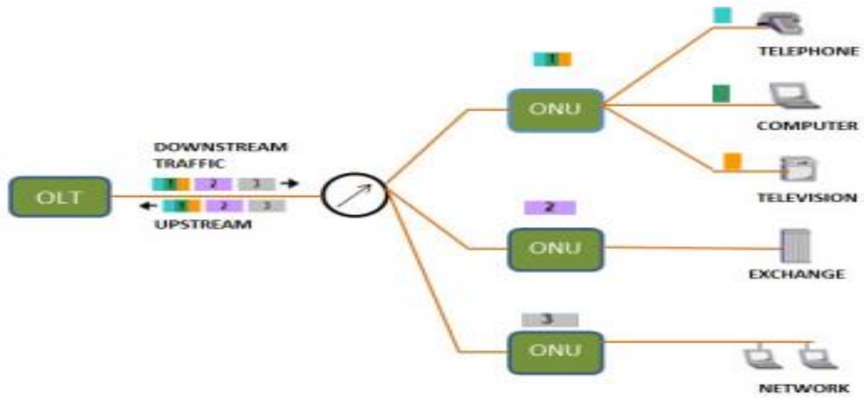


Figure 2.7 Time Division Multiplexing (Rajalakshmi et al., 2011).

2.6. Hybrid WDM/TDM PON

Hybrid WDM and TDM passive optical network (PON) enhance the functionality of passive optical network by combining the advantage of time division multiplexing (TDM) and wave division multiplexing (WDM). Multiple light wavelengths are employed in a hybrid WDM and TDM PON to transfer data between the optical line terminal (OLT) and the optical network terminals (ONTs) or ONUs. Because of distinct signal can travel at a different wavelength, this enables high-speed data transfer. TDM assign the time slot for data transmission between optical line terminal (OLT) and optical network unit (ONU). This makes several users to share effectively the available bandwidth. in hybrid WDM and TDM WDM is often used for downstream transmission from the OLT to the ONUs and TDM is typically used to allocate time slots to ONUs for upstream transmission as shown in figure 2.8. In comparison to conventional PON topologies, the hybrid PON architecture's combination of WDM and TDM can offer a number of benefits. The greater data speeds are one of the main benefits. The Hybrid PON can reach more data capacity than standard PONs that employ a single wavelength of light because it uses many wavelengths to transport data. Hybrid WDM and TDM enable service provider to serve client over large geographical area and the transmission over long distance can also supported. Additionally, by effectively sharing the available bandwidth among several users the Hybrid PON can improve bandwidth utilization. The combination of WDM and TDM technologies can efficiently allocate bandwidth to meet the needs of different users and applications (Priyeash & Nadu, 2020).

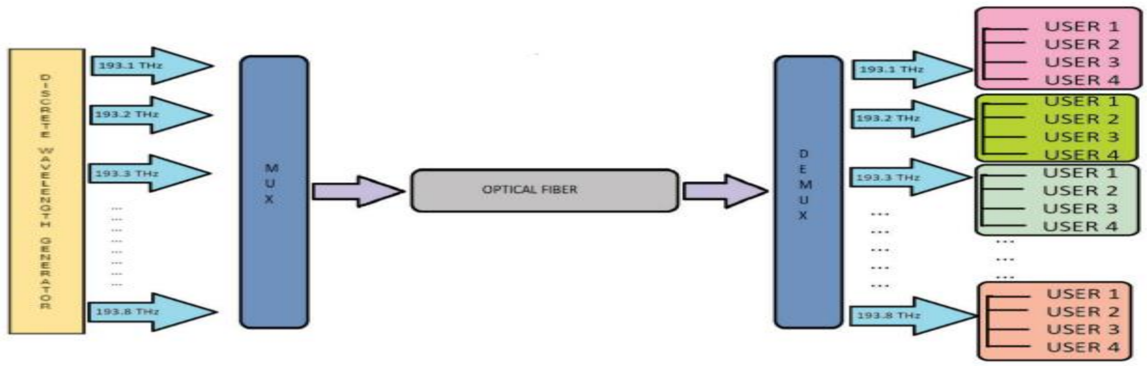


Figure 2.8 Hybrid passive optical network (Priyeash & Nadu, 2020)

2.7. Passive Optical Networks (PONs)

In telecommunications passive optical network(PON) is used to give homes and businesses high-speed broadband internet access. It's a fiber-optic network that distributes data over a shared infrastructure and it's known as passive because no active components are utilized in signal distribution. A single optical fiber connects several end users in a PON. An Optical Line Terminal (OLT), located in a central office is connected to the optical fiber and responsibility to receive and send data to the end users. The optical line terminal(OLT) is connected to ONU using optical distribution network as shown in figure 2.9.

At the end-user side, an Optical Network Unit (ONU) or Optical Network Terminal (ONT) is used to convert the optical signal back to an electrical signal. The ONU/ONT is connected to the user's device such as a computer, router, or modem(Olmos et al., 2012)

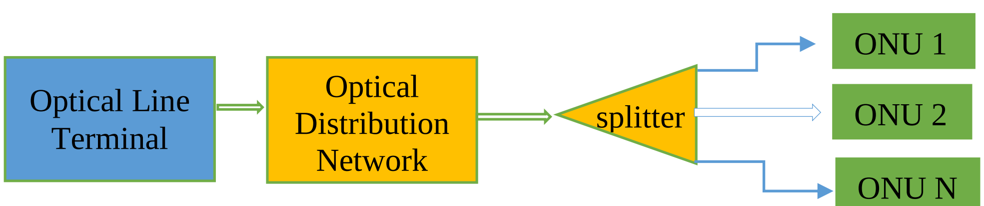


Figure 2.9 Block diagram of passive optical network

2.8. Radio over Fiber (RoF) Technology

Radio over fiber (RoF) technology is a technology that enables the transmission of radio frequency (RF) signals over optical fibers. This technology has gained acceptance due to its advantages in terms of long-distance signal transmission, low signal loss, and reduced electromagnetic interference. It's mainly used in various applications, including wireless communication systems, radar systems, and distributed antenna systems (DAS) for cellular networks(Apostolopoulos et al., 2018).

2.8.1. Applications of RoF Technology:

- ✓ Wireless Communication Systems: To increase signal quality and extend coverage, RoF is commonly utilized in satellite communication, Wi-Fi systems, and cellular networks.
- ✓ Radar Systems: RoF makes it possible for radar signals to be sent across great distances, improving surveillance and detection capabilities for defense and aerospace applications.
- ✓ Distributed Antenna Systems (DAS): - RoF technology enhances mobile user connectivity by assisting in the efficient distribution of wireless signals throughout large buildings, stadiums, or campuses.
- ✓ 5G Networks: RoF provide high speed and low latency service which is important for application like IoT, smart cities and autonomous vehicles which support 5G network.

2.9. Optical Access Technologies for Fronthaul

Optical access technology for fronthaul refers to the use of optical fibers to connect radio access network (RAN) device, such as small cells or remote radio heads, to centralized baseband processing units. This technology is essential to contemporary wireless networks, particularly in 5G deployments, since it offers the high bandwidth, low latency, and scalability that RAN elements need for effective communication. Time division multiplexing (TDM), wavelength division multiplexing (WDM), and Ethernet-based solutions like Ethernet fronthaul (EFH) and Ethernet over fiber (EoF) are important optical access technologies for fronthaul. Each has it is own benefit and the selection process is determined by things like network architecture, capacity needs, and budgetary constraints. When building a transport network, optical fibers with low latency and Tera bit per second (Tbps) bandwidth capacity are seen to be the most promising alternative (Jaffer et al., 2020).

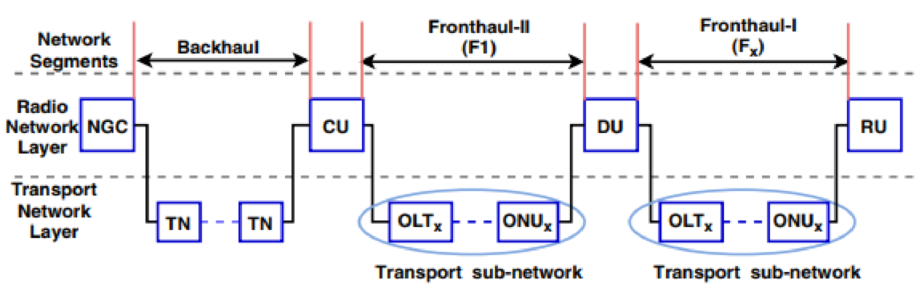


Figure 2.10 Transport network solution for 5G (Jaffer et al., 2020).

2.10. Related Work

The author of (Wey et al., 2018) reviewed evolving and future PON technologies for 5G transport systems and investigated coherent WDM-PON system. The transport network layer specification for 5G deployments is currently the main focus of the 5G New Radio (NR) sector. Because of their point-to-multipoint architecture, passive optical networks (PONs) are a popular option for extensive global deployment and effective utilization of fiber resources. The present requirements for 5G wireless transport, optical access technologies, and standards development initiatives specifically for 5G transport are also reviewed in this study. The author is not considering the effect of high data rate and different fiber length. Although the document describes PON's promise for 5G, it is devoid of empirical data and a detailed performance study on how well these implementations are working and the scalability of PON solutions to handle future increases in data rates is not well discussed.

In (Kim et al., 2018) the author demonstrated high-speed and low latency PON enabled by time controlled-tactile optical access technology supporting channel bonding and low-latency DBA for the accommodation in 5G mobile, business, and residential services. The author also introduces a channel bonding technique that allows multi-speed ONUs within a single (ODN). The guaranteed bandwidth of the optical link between OLT and ONU was demonstrated by using multilane channel bonding. On other hand a PON powered by time-controlled-tactile optical access (TIC-TOC) technology, which uses channel bonding in a single optical distribution network (ODN) to provide 48-hour real-time packet transmission up to 50 Gb/s without packet loss. The performance of the PON is demonstrated using a split ratio of 1:64 and a 20 km reach. Even if the author considers BER for performance analysis the performance of PON for 5G transport network is not analyzed using different performance metric such as quality factor, error vector magnitude and Symbol error rate.

In (Kumari et al., 2021) the author discuss about a novel multiplexing system has been designed to combine WDM and TDM into what is referred to as Time and Wavelength Division Multiplexing (TWDM). The suggested architecture provides a high-speed and long-range communication solution by combining a multi-color LDs-based VLC system with a TWDM-PON system. This system aims at improving the reach of the system as well as its bandwidth. This technique utilizes m-QAM OFDM modulations for both downstream and upstream directions, achieving high data rates of 120 Gbps, 100 Gbps, and 80 Gbps with 16-, 32-, and 64-QAM modulations respectively over 10 m VLC and 10 km fiber links. The evaluation is based on Bit Error Rate (BER) and EVM% with respect to received power and distance. The latency occurred by dynamic bandwidth allocation is not discussed in the case of time division multiplexing(TDM).

In (Bassoung et al., 2021) Author of paper state that, several units are served from an optical fiber after the NRO, through the insertion of optical couplers. This architecture is also called "G-PON" because it is an interconnect technology has very high speed. A single fiber from central serves a fiber group at a share point. It is thus possible to serve multiple homes from a single fiber. This architecture offers the advantage of limiting the number of fibers to be deployed but the equipment (splitter) functioning as a hub, each house served receives all information passing over the line. The author only analyzes the performance of PON under NRZ (Non-Return to Zero) modulation scheme and higher order modulation is not considered.

In (Suzuki et al., 2017) paper state that coherent passive optical network (PON) technology is reviewed in detail with a focus on data rates ranging from 100 Gb/s to 1 Tb/s. This is essential to meet the increasing bandwidth needs that will arise from the deployment of 5G and beyond (B5G) mobile networks. Typically, a loss budget of more than 29 dB is required in a practical ODN. In order to meet this requirement, coherent technology has been considered a potential candidate due to its inherent high receiver sensitivity nature at much higher bit-rates. The impact of nonlinear and linear impairments, including self-phase modulation (SPM) and cross-phase modulation (XPM), which become significant at higher power levels and data rates is not considered in this paper.

Table 2.1 Summary of related work.

Authors	Year	Titles	Contribution	Gaps
Kumari et al.,	2021	Performance analysis of symmetrical and bidirectional 40 Gbps TWDM-PON employing m-QAM-OFDM modulation with multi-color LDs based VLC system	achieving high data rates (40/40 Gbps) using QAM signals over extended distances	The latency occurred by dynamic bandwidth allocation is not discussed in the case of time division multiplexing(TDM).
Wey et al.,	2018	Passive Optical Networks for 5G Transport Technology and Standards	Analysis of various (PON) technologies suitable for 5G transport and challenges for 5G transport.	High data rate and different fiber length is not considered.
Kim et al.,	2018	High Speed and Low Latency Passive Optical Network for 5G Wireless Systems.	introduces a channel bonding technique that allows multi-speed ONUs within a single (ODN).	Performance analysis the performance of PON for 5G transport network is not analyzed using different performance metric such as quality factor, error vector magnitude and Symbol error rate.
Suzuki et al.,	2017	100G to 1T Based Coherent PON Technology	The paper provides a coherent PON technology using WDM , which is crucial for meeting the growing bandwidth demands of emerging applications such as fixed-mobile convergence in 5G and beyond 5G (B5G) networks	The impact of nonlinear and linear impairments, including self-phase modulation (SPM) and cross-phase modulation (XPM), which become significant at higher power levels and data rates is not considered in this paper. .
Bassoung et al	2021	Performance Analysis of a Passive FTTH-PON System Using Hybrid OTDM/WDM Multiplexing	hybrid OTDM/WDM architecture offers the advantage of limiting the number of fibers to be deployed but the equipment (splitter) functioning as a hub, each house served receives all information passing over the line.	The author only analyzes the performance of PON under NRZ (Non-Return to Zero) modulation scheme and higher order modulation is not considered

CHAPTER THREE

MATERIALS AND METHODS

3.1. Introduction

The approach for modeling a Design and Performance Analysis of WDM PON Based on Heterodyne Receiver for 5G Transport has been designed and simulated using OptiSystem 20 software with several modulation schemes such as QPSK, 8-PSK and 16-PSK. It is used to design, construct and simulate the WDM PON Based on Heterodyne Receiver.

3.2. Material

The OptiSystem Software is used in this project. OptiSystem is a software platform which allows users to design, performance evaluation, test, and simulate optical links at the transmission layer of recent optical networks.

3.3. Methodology

The following formal approaches are used in the thesis to achieve the aforementioned goals.

Literature review: In this thesis Previous scholarly or expert research on the topic is intrinsically tied. Therefore, reading the works of these academics and learning pertinent information about the issue are crucial. A range of sources, such as papers, books, journals, the internet, etc., are reviewed. As a result, reading articles, conference papers, books, journals, and looking through numerous online sources for relevant topics defines (i.e. Design and Performance Analysis of WDM PON Based on Heterodyne Receiver for 5G Transport).

Problem Identification: based on the paper reviewed from different journals, articles and conferences the problem (research gaps) are identified for research study.

System Designing: The systems are designed for the proposed study after the research gap has been identified.

Result and Discussion: Discussions are held based on the results of the simulation, and the performance of the suggested techniques is also evaluated.

Documentation: The entire research study concludes by recommending an implicit recommendation and additional work to be done on the areas after examining the findings of the designed system.

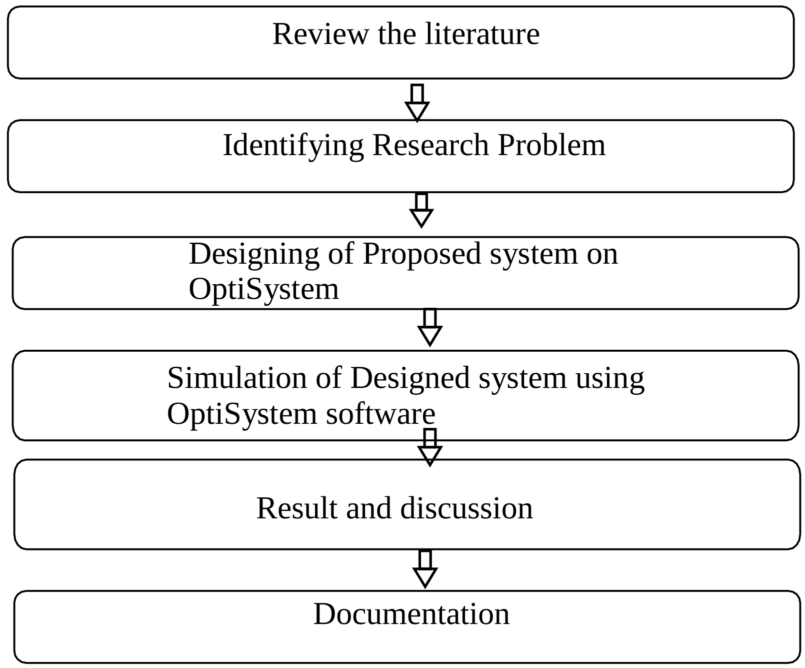


Figure 3.1 Methodology

3.4. System Model for Coherent Detection

The main idea behind the coherent detection method is to amplify the incoming signal by coupling it to a local generated continuous wave (CW) optical field. This continuous wave (CW) is generated by device called local oscillator. When two things are mixed together, when waves with frequency w1 and w2 are merged, additional waves with frequencies equal to 2w1, 2w2, and w1±w2 are created. For coherent light wave systems, all frequency components except w1 - w2 are filtered out at the receiver. A local oscillator (LO) is the apparatus which is a narrow-linewidth laser that generates the CW signal.

To understand how this mixing can increase the coherent receiver performance, let us consider the electric field of the transmitted optical signal to be a plane wave having the form

$$E_s = A_s cos[\omega_s t + \varphi_s(t)] \tag{3.1}$$

where $A_s$is the amplitude of the optical signal field, ω_st is the optical signal carrier frequency, and φ_s(t) is the phase of the optical signal. So in order to send information, one can modulate the amplitude, frequency, or phase of the optical carrier.

In coherent light wave systems, the receiver first combines an incoming information-bearing signal with a locally generated optical wave before detecting the resulting signal. There are four demodulation format Based on how the optical signal is combined with the local oscillator (which gives in heterodyne or homodyne detection) and how the electrical signal is detected (either synchronously or asynchronously). On the photodetector's surface, the information-bearing and local-oscillator signals are mixed before photo detection going on.

If the local-oscillator (LO) field has the form

$$E_{LO} = A_{LO} cos[\omega_{LO} t + \varphi_{LO}(t)] \tag{3.2}$$

where A_{LO} is the amplitude of the local oscillator field, ω_{LO} is the local-oscillator frequency and $\varphi_{LO}(t)$ is local-oscillator phase, then the square of the total electric field of the signal that is falling on the photodetector is proportional to the amount of intensity that is detected $I_{coh}(t)$.

$$I_{coh}(t) = (E_s + E_{LO})^2 \tag{3.3}$$

$$\frac{1}{2} A_s{}^2 + \frac{1}{2} A_{LO}{}^2 + A_s A_{LO} \cos[(\omega_s - \omega_{LO})t + \varphi(t)] \, cos\theta(t) \tag{3.4}$$

where $\varphi(t) = \varphi_s(t) - \varphi_{LO}(t)$ is the relative phase difference between the local oscillator signal and the incoming information-bearing signal and $\cos\theta(t) = \frac{E_S . E_{LO}}{|E_S||E_{LO}|}$ reflects the mismatch of the polarization of the local-oscillator wave and the signal wave.

$$P(t) = P_s + P_{LO} + 2\sqrt{PsP_{LO}} \cos[(\omega_s - \omega_{LO})t + \varphi(t)]\cos\theta(t) \tag{3.5}$$

where P_s is the signal optical power and P_{LO} is local-oscillator optical powers with $P_{LO} >> P_s$.

Thus we realize that the difference of angular-frequency $\omega_{IF} = \omega_S - \omega_{LO}(t)$ is an intermediate frequency, and the time-varying phase difference between the signal and local-oscillator levels is given by phase angle (t).

3.5. Homodyne Detection

The particular case of homodyne detection occurs when the signal-carrier and local-oscillator frequencies are same, or when $\omega_{IF} = 0$ and equation 3.5 is simplified to

$$P(t) = P_s + P_{LO} + 2\sqrt{P_S P_{LO}} \cos\varphi(t) \cos\theta(t) \tag{3.6}$$

As seen by the equation above, homodyne detection sends the signal straight to the baseband frequency, avoiding the need for further electrical demodulation. The most sensitive coherent systems are produced by homodyne receivers. However, because an optical phase-locked loop is required to control the local oscillator, they are also the most challenging to construct. Furthermore, the local-oscillator lasers must have the same frequency as the signal, which imposes very strict restrictions on these two optical sources. So, to transfer information, one can either use OOK modulation schemes (changing the signal level Ps while keeping φ(t) constant) or PSK modulation schemes (varying the signal phase$\varphi_s(t)$ while keeping P_S constant).

3.6. Heterodyne Detection

An optical phase-locked loop is not required for heterodyne detection since the intermediate frequency, ω_{IF} is not zero. Heterodyne receivers are therefore significantly simpler to implement than homodyne receivers. However, this simplification comes at the cost of a 3-dB reduction in sensitivity when compared to homodyne detection.

Let's examine about the receiver's output incident. We can omit the first term on the right side of Equation 3.5 because P_s<<P_{LO}. The receiver output incident then contains a dc term given by

$$i_{dc} = \frac{\eta q}{hv} P_{LO} \tag{3.7}$$

where, η is the quantum efficiency, q is the electron charge = 1.60218 ×10^{-19}coulombs, h is Planck's constant = 6.6256 ×10^{-34}, and v is the frequency.

The time varying IF term given by

$$i_{IF} = \frac{2\eta q}{hv} P_s P_{LO} cos[\omega_{IF} t + \varphi(t)] cos\theta(t) \tag{3.8}$$

The receiver typically filters out the dc current while amplifying the IF current. The information is then extracted from the boosted current using conventional RF demodulation methods.

According to the heterodyne detection notion discussed, it is obvious that employing heterodyne detection components to construct a 5G transport architecture is more cost-effective than using homodyne devices and more comfortable with PON technology for transportation of 5G.

Heterodyne detection supports three types of modulation techniques, which are OOK, FSK, and PSK. This section will provide a lookup of the modulation techniques along with a comparison of the BER for each scheme as shown in figure 3.4. By considering BER of $10^{-9,}$ the receiver sensitivity which have less photon number on photodetector surface to retrieve information is selective as best receiver. The implementation of heterodyne receiver detection is either synchronous or asynchronous.

3.6.1. Synchronous Heterodyne Detection

In this detection the received optical signal will be mixed with the local oscillator laser wave and the two mixed signal have different phase and amplitudes.

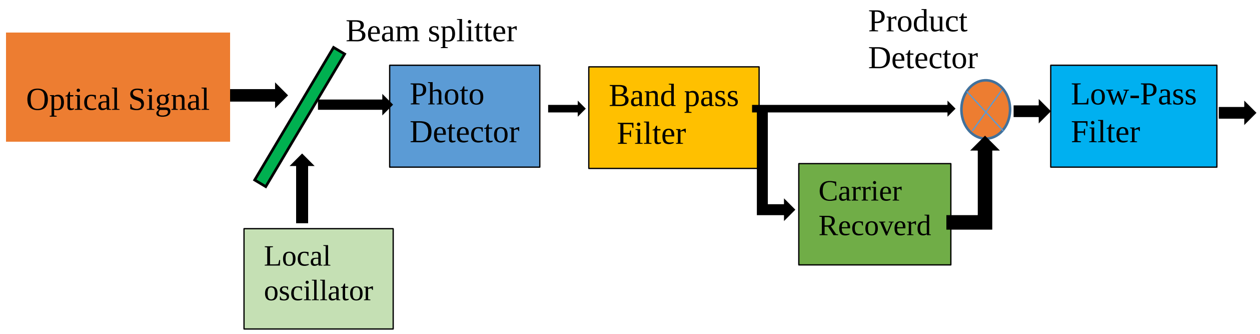


Figure 3.2 Synchronous detection of heterodyne receiver.

This mixed signals passes through photodetector into a Band pass filter and then it will be multiplied by carrier recovery signal and the generated signal will have both intermediate frequency and carrier frequency. The low pass filter then retrieves the signal with intimate information.

3.6.2. Asynchronous Heterodyne Detection

This detection is not undergoing carrier recover process. The current generated at photodiode is passed through BPF centered at intermediate frequency. The envelope detector rectifies the IF signal, capturing the amplitude variations (envelope) which contain the baseband information and the low pass filter then retrieves the original signal that contains desired information as shown in figure 3.3.

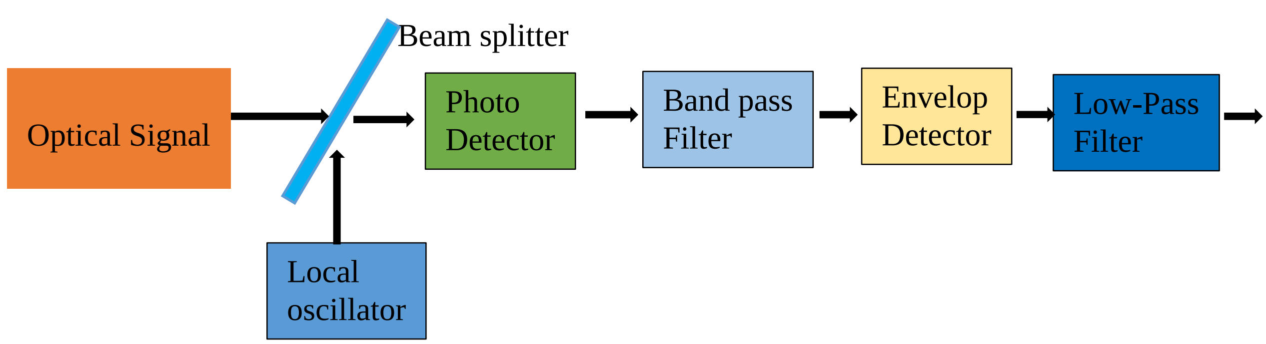


Figure 3.3 Asynchronous detection heterodyne receiver.

3.7. Nonlinear and Linear Impairments in Optical Fiber

Pulse propagation inside this transmission system can be described by the nonlinear Schrödinger equation (NLSE). When modeling pulse propagation in a single mode fiber, the Nonlinear

Schrodinger (NLS) wave equation is employed. For extended fiber lengths, the NLS wave equation is usually obtained under a few approximations on the guiding medium's waveguide properties. In an optical fiber communication system, the non-linear Schrodinger equation 3.9 describes the pulse envelope in time t at the spatial position z, A(z, t) propagating from the transmitting to the receiving end(Abdullahi Mohammed et al., 2018).

$$\frac{\partial}{\partial z}\mathrm{A(z,t)} = -\frac{\alpha}{2}A(z,t) + \beta_1\frac{\partial}{\partial z}\mathrm{A(z,t)} - j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}A(z,t) + \frac{\beta_3}{6}\frac{\partial^3}{\partial t^3}A(z,t) - j\gamma|A(z,t)|^2A(z,t) + j\gamma T_R|A(z,t)|^2A(z,t) + \frac{\gamma}{\omega_o}|A(z,t)|^2A(z,t) \tag{3.9}$$

A is the pulse envelope in spatial position z and in time t.

β_1 in the first order dispersion parameter causes pulse delay due to polarization mode dispersion.

β_2 is the second order dispersion parameter causes pulse broadening due to chromatic dispersion.

γ is propagation constant

α is the attenuation coefficient of the fiber

$-\frac{\alpha}{2}A(z,t)$ is Linear attenuation.

$-j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}A(z,t)$ Second order dispersion

$\frac{\beta_3}{6}\frac{\partial^3}{\partial t^3}A(z,t)$ Third order dispersion

$j\gamma|A(z,t)|^2A(z,t)$ Kerr effect.

$j\gamma T_R|A(z,t)|^2A(z,t)$ Stimulated Raman Scattering

$\frac{\gamma}{\omega_o}|A(z,t)|^2A(z,t)$ Self-steepening effect

When the pulse width is greater than 1ps, equation 3.9 can be considerably simplified (as indicated below) because the Raman effect term and the self - steepening effect term are negligible compared to the Kerr effect term

$$\frac{\partial A}{\partial z} + \beta_1\frac{\partial A}{\partial z} - \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2}A = i\gamma|A|^2A \tag{3.10}$$

From the equation 3.10 we can obtain effects in optical fibers and we can classify them as:

- ✓ Nonlinear effects, which are intensity (power) depended.
- ✓ Linear effects, which are wavelength depended.

3.7.1. Nonlinear impairments

Nonlinear impairments arise as a result of the fiber's refractive index being dependent on signal intensity. These impairments which include self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM) and become significant at high power levels.

Self-Phase Modulation (SPM): a pulse's intensity-dependent phase shift causes SPM. SPM is produced when light moves across optical fibers with varying refractive index. The high peak power of signal pulses elevates the refractive index of silica, resulting in a reduced group velocity (kaminow & Le, 2002).

The expression for the nonlinear phase shift caused by SPM is given by equation 3.11:

$$\phi_{NL} = \gamma P L_{eff} \tag{3.11}$$

Where

γ is nonlinear coefficient measured in $1/_{w.km}$.

P is optical power (in w).

L_{eff} is effective length of fiber given by

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha} \tag{3.12}$$

Cross-phase modulation(XPM): happens when the phase of one co-propagating channel is influenced by the intensity of another wavelength channel (Ali et al., 2022).

In a multichannel system, the excess bandwidth generated by the XPM effect is given by equation 3.13:

$$\frac{\Delta\phi_{nl}}{\Delta t} = \gamma L_{eff}\frac{\Delta P_0}{\Delta t} + 2\gamma L_{eff}\frac{\Delta P_1}{\Delta t} \tag{3.13}$$

Where

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{3.14}$$

$\Delta\phi_{nl}$ is the phase change due to optical power.

γ is nonlinear parameter.

L_{eff} is nonlinear effective length.

$\frac{\Delta P_0}{\Delta t}$ Rate of change of power in the first channel.

$\frac{\Delta P_1}{\Delta t}$ Rate of change of power in the second channel.

A_{eff} is the effective area of the optical mode in the fiber.

n_2 is coefficient of nonlinear refractive index

λ the wave length of light.

In a WDM system, XPM converts power fluctuation in a particular wavelength channel to phase fluctuations in other co-propagating channels. This leads to broadening of pulse.

Four-Wave Mixing (FWM): The beating of light at various frequencies in multichannel transmission causes the channels' phases to change, which creates modulation sidebands at new frequencies that are referred to as four-wave mixing (kaminow & Le, 2002).

If three components propagate at frequencies $\mathcal{F}_i$, $\mathcal{F}_j$and $\mathcal{F}_k$, a new wave is generated at new frequency which is given in equation 3.15

where

$$\mathcal{F}_{ijk} = \mathcal{F}_i + \mathcal{F}_j - \mathcal{F}_k. \tag{3.15}$$

The FWM efficiency is given by,

$$\eta = \left|\frac{1-\exp(-[\alpha+\Delta\beta]L)}{(\alpha+i\Delta\beta)L}\right|^2 \tag{3.16}$$

$\Delta\beta$ is the difference in the propagation constant between the channels due to the fiber dispersion.

$$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_{ijk} \tag{3.17}$$

α is the coefficient of fiber attenuation.

L is fiber length.

Efficiency is maximum when there is perfect phase matching ($\Delta\beta=0$). In this scenario, the phase mismatch term vanishes and the attenuation (α) and fiber length (L) are the primary determining factors.

$$\eta_{\Delta\beta=0} = \left|\frac{1-\exp(-\alpha L)}{\alpha L}\right|^2 \tag{3.18}$$

Nonetheless, using transmission fiber with large local dispersion reduces the phase matching between WDM channels, which is the most efficient way to prevent FWM crosstalk.

3.7.2. Linear impairments

Linear impairments in optical fibers are defined as signal degradation effects that scale proportionally with the signal strength and do not depend on the nonlinear properties of the signal. The fundamental linear fiber impairment in optical fiber is attenuation and dispersion.

Attenuation: Attenuation is the reduction in signal power that occurs during transmission which means the decreasing level of the signal power with increasing length. Standard single-mode fibers

(SSMFs) have an average attenuation coefficient of 0.2 dB/km over the C-band frequency spectrum. Generally expressed as a dB/km loss coefficient(Porto da Silva et al., 2017).

The attenuation can be mathematically described by the equation 3.19:

$$P(z) = P_0 e^{-\alpha z} \tag{3.19}$$

Where

$P(z)$ is the power at distance z.

P_0 is the initial power

α is the attenuation coefficient.

Z is the distance traveled through the fiber

Dispersion: Dispersion broadens the pulse by causing the signal's various frequency components to move at various speeds. Two primary categories of dispersion exist: polarization mode dispersion and chromatic dispersion (Ali et al., 2022).

Chromatic Dispersion: Light travels at varying speeds in different wavelengths, which causes chromatic dispersion. The dispersion can be quantified by the dispersion parameter D (in ${}^{P_s}/_{(nm.km)}$. The equation 3.20 provides the pulse broadening caused by chromatic dispersion:

$$\Delta T = D.L.\Delta\lambda \tag{3.20}$$

Where

ΔT is pulse broadening.

D is Dispersion parameter.

L is the length of fiber.

$\Delta\lambda$ is spectral width of the fiber.

Polarization mode dispersion: The term polarization mode dispersion (PMD) refers to the phenomenon whereby imperfections in the fiber lead to varying polarizations traveling at different speeds. The differential group delay (DGD) is used to define PMD.

The average DGD can be described by:

$$DGD_{rms} = D_{PMD}\sqrt{L} \tag{3.21}$$

D_{PMD} is PMD coefficient.

L is length of the fiber.

3.8. Analysis of BER and Photon for Heterodyne Receiver Scheme.

In communication system BER is used to measure the performance and quality of the signals. Photon is a particle representing quantum of light or other electromagnetic radiation and carries energy proportional to radiation frequency. BER and calculation of number of photon for three Modulation Technique (PSK, OOK and FSK) is discussed as shown below.

3.8.1. BER and Photon for PSK Heterodyne System.

The BER for PSK synchronous heterodyne receiver is given by

$$BER = \frac{1}{2}\, erfc\left(\sqrt{\eta \overline{N_p}}\right) \tag{3.22}$$

From equation (3.9) by considering BER=$10^{-9}$and quantum efficiency $\eta = 1$ the number of photon required is

$\overline{N_p} = erfc^{-}\,(2 \times 10^{-9})$

$\overline{N_p} = 18$

From this to attain BER of 10^{-9} 18 photon is required.

In the case of asynchronous heterodyne receiver BER is given by

$$BER = \frac{1}{2}\ \exp\left(-\eta\overline{N_p}\right) \tag{3.23}$$

From equation (3.10)by considering BER=10^{-9} and quantum efficiency $\eta = 1$

$2 \times 10^{-9} = \exp\left(-\overline{N_p}\right)$

Taking logarithm of both side.

$\overline{N_p} = 9 \times ln10 - ln2$

$\overline{N_p} = 20$

3.8.2. BER and Photon for OOK Heterodyne System.

The BER for OOK synchronous heterodyne receiver is given by

$$BER = \frac{1}{2}\, erfc\left(\sqrt{\frac{1}{2}\eta\overline{N_p}}\right) \tag{3.24}$$

From equation (3.11) by considering BER=10^{-9} and quantum efficiency $\eta = 1$

$\overline{N_p} = 2 \times erfc^{-}(2 * 10^{-9})$

$\overline{N_p} = 36$

For asynchronous heterodyne receiver BER is given by

$$BER = \frac{1}{2}\ \exp\left(-\frac{1}{2}\eta\overline{N_p}\right) \tag{3.25}$$

From equation (3.12) by considering BER=10^{-9} and quantum efficiency $\eta = 1$

$$2 \times 10^{-9} = \exp\left(-\frac{1}{2}\overline{N_p}\right)$$

Taking logarithm of both side.

$$\overline{N_p} = 2 \times (9ln10 - ln2)$$

$$\overline{N_p} = 40$$

3.8.3. BER and Photon for FSK Heterodyne System.

The BER for FSK synchronous heterodyne receiver is given in equation (3.11)

$$BER = \frac{1}{2}\ erfc\left(\sqrt{\frac{1}{2}\eta\overline{N_p}}\right)$$

From equation (3.11) by considering BER=10^{-9} and quantum efficiency $\eta = 1$

$$\overline{N_p} = 2 \times erfc^{-}(2 * 10^{-9})$$

$$\overline{N_p} = 36$$

For asynchronous heterodyne receiver BER is given in equation (3.12)

$$BER = \frac{1}{2}\ \exp\left(-\frac{1}{2}\eta\overline{N_p}\right)$$

From equation (3.11) by considering BER=10^{-9} and quantum efficiency $\eta = 1$

$$2 \times 10^{-9} = \exp\left(-\frac{1}{2}\overline{N_p}\right)$$

Taking logarithm of both side.

$$\overline{N_p} = 2 \times (9ln10 - ln2)$$

$$\overline{N_p} = 40$$

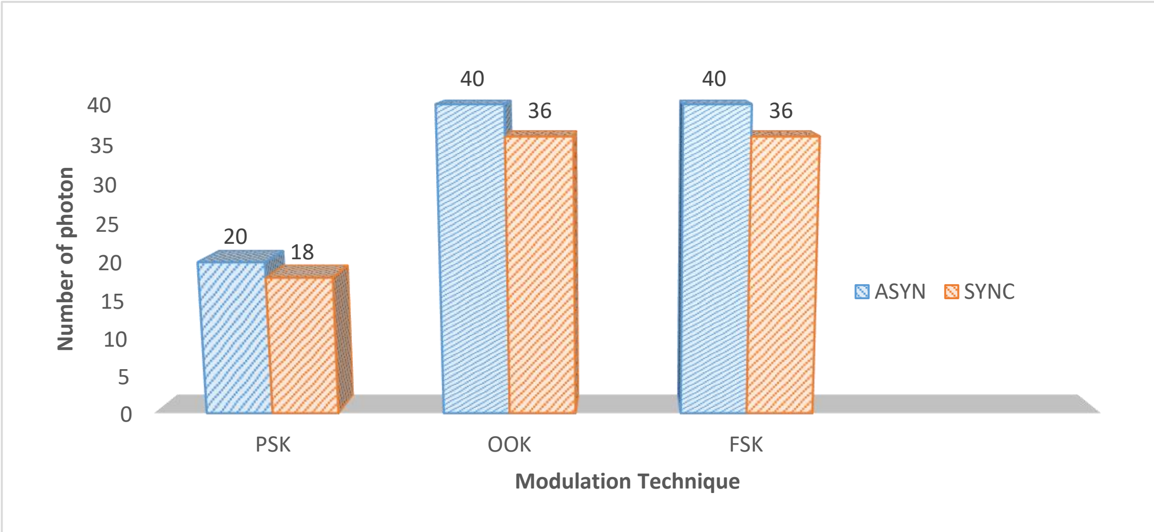


Figure 3.4 comparison of number of photon for different modulation for BER of 10^{-9}

PSK is require less number of photon to attain BER of 10^{-9} so it is preferable.

3.9. System Model for Proposed WDM Passive Optical Network.

This section provides a concise summary of the simulation in OptiSystem, with all critical parameters derived from the standardized characteristics of Passive Optical Networks.

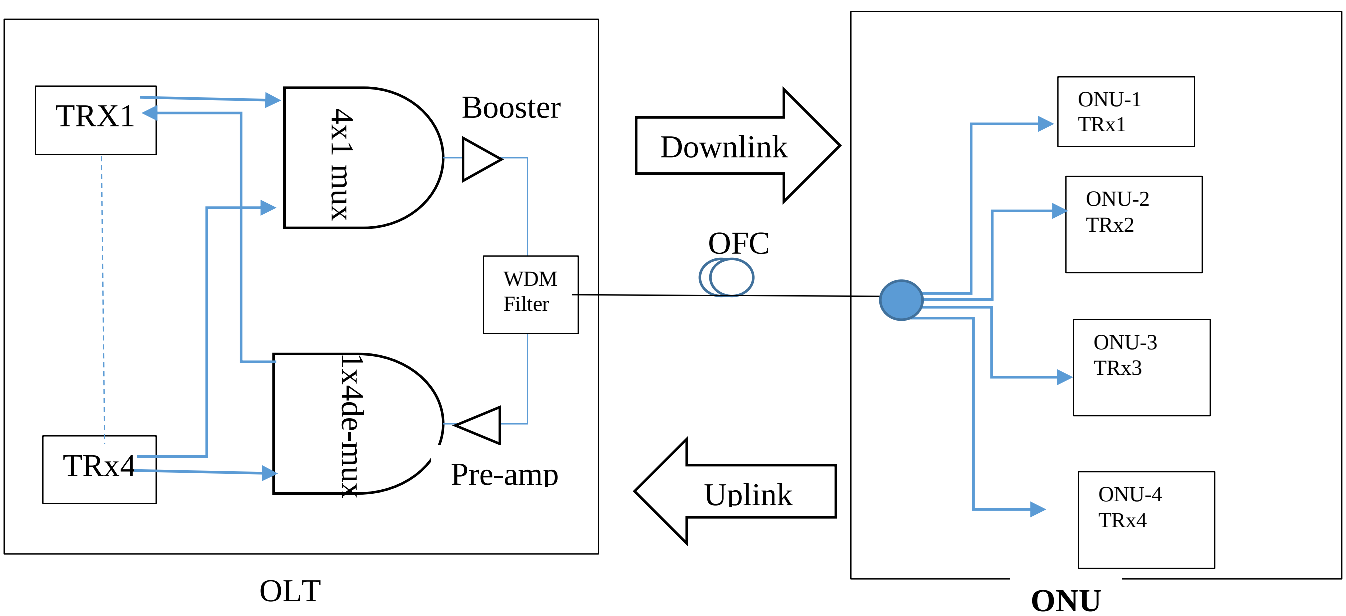


Figure 3.5 Topology of WDM PON Network

In order to meet the high bandwidth requirements of 5G and beyond 5G (B5G) transport networks, the WDM-PON scheme employing DP-PSK has been investigated. Four wavelengths are used in this technique, and each one serves a tiny cell at a transport data rate of 100 Gbps. As a result, 5G and B5G networks can achieve data throughput of 400 Gbps (100 Gbps per wavelength × 4 wavelengths). Figure 3.5 shows the block diagram for a 100 Gbps per wavelength WDM-PON network over a 100–200 km single-mode fiber (SMF). Optical couplers are located at the end of the 100 km to 200 km SMF access span and connect each ONU to the Optical Line Terminal (OLT) on a specific wavelength. A 100 Gbps DP-PSK optical transceiver was used on the OLT side. In addition, a Gaussian WDM optical filter, an optical multiplexer/de-multiplexer (MUX/DEMUX), a booster amplifier for the downlink (DL), and a pre-amplifier for the uplink (UL) were used. Standard erbium-doped fiber amplifiers (EDFAs) called booster and pre-amplifiers are placed at the OLT to eliminate the need for extra power in the optical distribution network (ODN) and reduce power consumption at the ONUs.

3.10. Components Required in Design of WDM Passive Optical Networks

A Wavelength Division Multiplexing (WDM) Passive Optical Network (PON) would be modeled using virtual representations of actual components using OptiSystem, a software tool for simulating and developing optical communication systems. The following are the main elements that are commonly utilized in OptiSystem while designing such networks:

Pseudo-Random Binary Sequence (PRBS): Generates Binary Bits to be transmitted to the ONU from the OLT & vice-versa. The PRBS describes an algorithm that uses mathematical formulas to produce a sequence of random numbers with characteristics resembling those of random data. The program generates a series of numbers that roughly matches the properties of random data.

The N- bit generated by PRBS is modeled as

$$N = T_w B_r \tag{3.26}$$

$$N_G = N - n_l - n_t \tag{3.27}$$

where

N =number of sequence bit

T_w Global Time Window

B_r bitrate parameter

N_G : is the number of bits, n_l the number of leading zeros, and n_t the number of trailing zeros

Continuous Wave Lasers: CW lasers produce continuous emission of laser that carry information in communication system. This laser can transfer signals over long distances with little distortion and will be used as a carrier signal in a PON at different wavelengths.

Multiplexer: In optical communication, a multiplexer is a device that combines multiple optical signals of different wavelengths into a single optical fiber core. This manage the costs and make the communication system easy by utilizing efficiently the permitted bandwidth.

Optical Fiber: Optical fiber is the Transmission Media in which light is carrying information from transmitter and propagates to the receiver. The signals propagate through optical fiber is not disturbed by electric field and best media in current communication.

De-multiplexers: It is a device that divides the multiple wavelength transmitted by one core into several signals or wave length, each of which contains a different wavelength. In Passive Optical Networks, a de-multiplexer is used to assign multiple wavelengths to different ONUs.

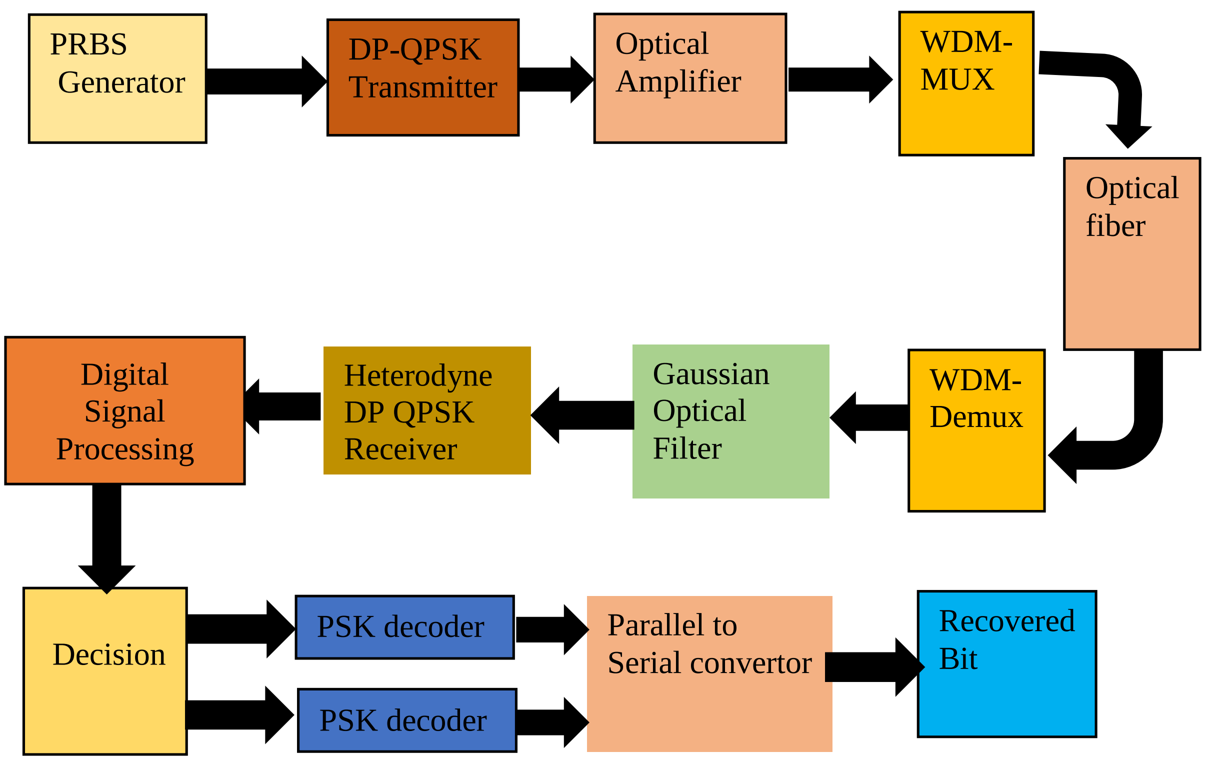


Figure 3.6 Transmission and receiving component of OLT and ONU

As seen in figure 3.6, the block diagram is divided into optical and electrical parts. The optical component consists of optical DP-QPSK transmitter to modulate the pseudo-random binary sequence (PRBS) data, Optical amplifier which is used for boosting the optical signal strength. WDM-mux to combine multiple optical signal of different wavelengths into a single optical fiber core, WDM-De-mux that divides the multiple wavelength transmitted by one core into several signals or wave length, heterodyne DP-QPSK receiver to receive the upstream signal and Gaussian optical filter. Second the electrical side include digital signal processor (DSP) to help recovery of incoming signals, Additionally, a decision component functions by processing the electrical signals, I and Q, that are received from the DSP stage and then normalizes each signal's electrical amplitude to the corresponding QPSK constellation and decides each received symbol using the normalized threshold settings. Two PSK sequence decoders are employed to demodulate and decode the sequence generated by decision component. Moreover, a parallel to serial (P/S) converter is used to combine the two input sequences into a single output sequence and finally bit recovery to recover bit by performing the direct error counting for one or more sweep iterations of a defined sequence length of bits.

3.11. Performance Parameter Utilized in PON Network

The quality of service provided by optical communication networks is gauged by specific parameters. The parameters that can be employed in this study to evaluate and assess the performance of each optical communication system discussed below.

Bit Error Rate (BER).

Bit Error Rate (BER) is performance measurement used for evaluating a digital communication system's accuracy by analyzing the error bit received in comparison with total number of bit transmitted. In communication systems, error rates show how frequently bit is distorted resulting from noise, interference, or distortion affecting the received data bits occur. The Bit Error Rate (BER) is a percentage that indicates how many incorrect bits are communicated relative to all bits transferred (Alam Jahangir S.M. et al., 2011).

$$BER_{M\_PSK} = \frac{2}{log_2\,(M)} Q(\sqrt{\frac{2E_b sin\left(\frac{\pi}{M}\right)}{N_O}}) \tag{3.28}$$

Where

BER_{M_PSK} bit error rate for m-aray PSK

$log_2\,(M)$ the number of bit per symbol for M-aray PSK

Q(x) = Q-function and it is defined by Gaussian probability distribution

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{X}^{\infty} e^{-\frac{t^2}{2}} dt \quad (3.29)$$

where

E_b : energy per bit

N_o: the noise power spectrum

$sin^2(\frac{\pi}{M})$ factor that depend on the number of symbol.

This general formula of m-array PSK is inversely proportional to the number of bit per symbol and directly proportional to Q-function.

Symbol Error Rate(SER)

Is performance measurement used in digital system which analyze the probability of incorrect detection or decoding of transmitted symbol. Symbol error occur when transmitted symbol is not coded correctly (Thrampoulidis et al., 2018).

Error Vector Magnitude

In ideal transmission the constellation point compiled at ideal location but due to some distortion the constellation point become depart from ideal position as shown in figure 3.7. the EVM measure how much the point deviate from the ideal position.

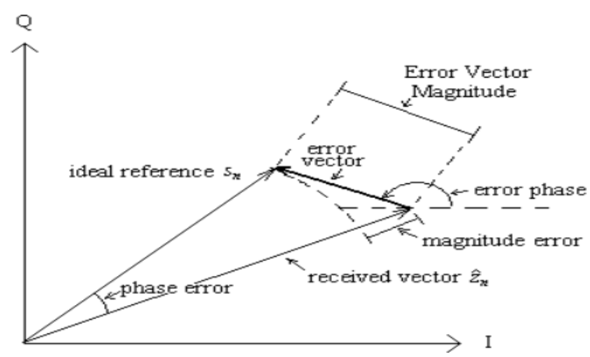


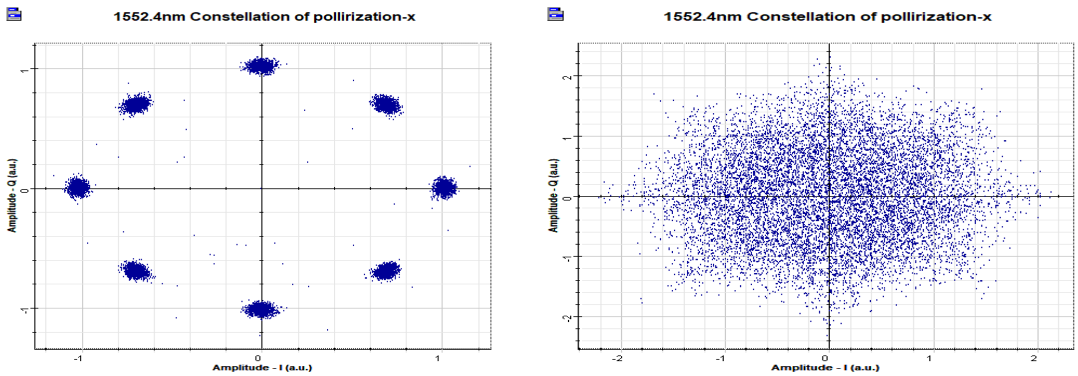
Figure 3.7 Error Vector Magnitude (Shafik et al., 2006)

Quality factor

The Q factor is a parameter that directly indicates the quality of an optical communication system. The higher the Q factor, the better the quality of the optical signal and the precise alignment of constellation point in ideal position.

Constellation diagram:

It is visual representation of distinct position of each symbol in I-Q plane. The spread and scattered of a symbol in plane that shown in figure 3.8(b) indicate that there is high noise and low signal, the condensed and tight of symbol that shown in figure 3.8(a) indicate high signal strength and low noise.



(a)　　　　　　　　(b)

Figure 3.8 Tight and good signal quality (a) scattered and low signal quality (b) of 8-psk

3.12. Simulation Design of DP-QPSK

DP-QPSK (Dual-Polarization Quadrature Phase Shift Keying) is a modulation format that boosts spectral efficiency and data transfer rate in optical communication.

In DP-QPSK the Light can be polarized in two orthogonal states typically horizontal and vertical and this polarization state of light double the data capacity.

Operational principle of DP-QPSK

For both horizontal and vertical polarization, the data stream is divided into in-phase (I) and quadrature (Q). With QPSK, each component independently modulates the optical carrier and the modulated carrier combined transmitted over transmission media which is Optical fiber cable in this case. Due to orthogonal polarization there is no interference with each other.

At the Receiver part the transmitted signal is split into two polarizations and demodulated using QPSK modulation. phase information is extracted by mixing incoming signal with local oscillator laser. To receive the original transmitted signal and to correct any affliction DSP technique is used. With its ability to handle larger data rates and more effective bandwidth utilization, DP-QPSK marks a significant leap in optical communications and is essential for meeting the growing demand for high-speed internet and data services. The DP-QPSK Transmitter transmit the signal which propagate through transmission link of optical fiber cable.

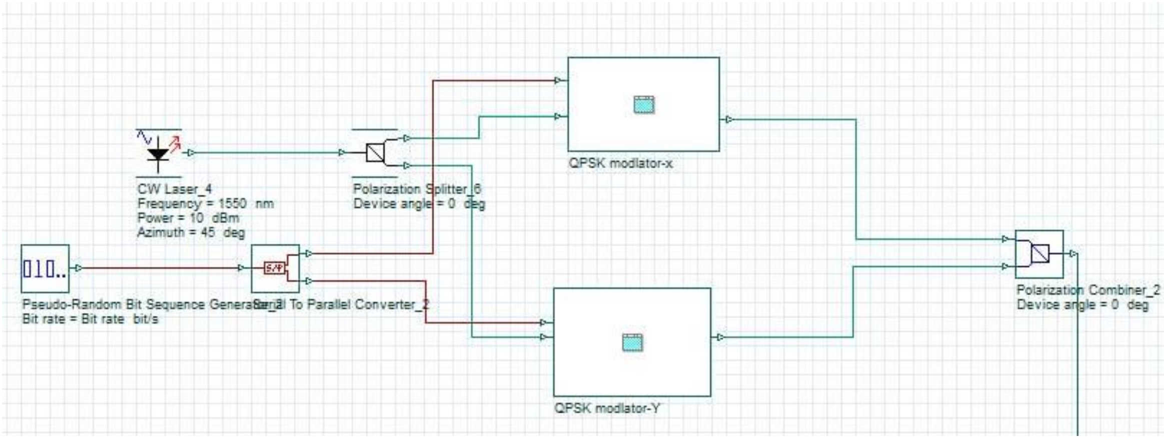


Figure 3.9 DP QPSK transmitter.

In this instance, polarization multiplexing is employed. A Polarization Beam Splitter (PBS) splits the laser output into two orthogonal polarization components, which are subsequently modulated independently by QPSK modulators and combined via a Polarization Beam Combiner (PBC) as shown in figure 3.9. After polarization combiner the signal transmit to single channel of WDM-Mux and for four channel four transmitter is required.

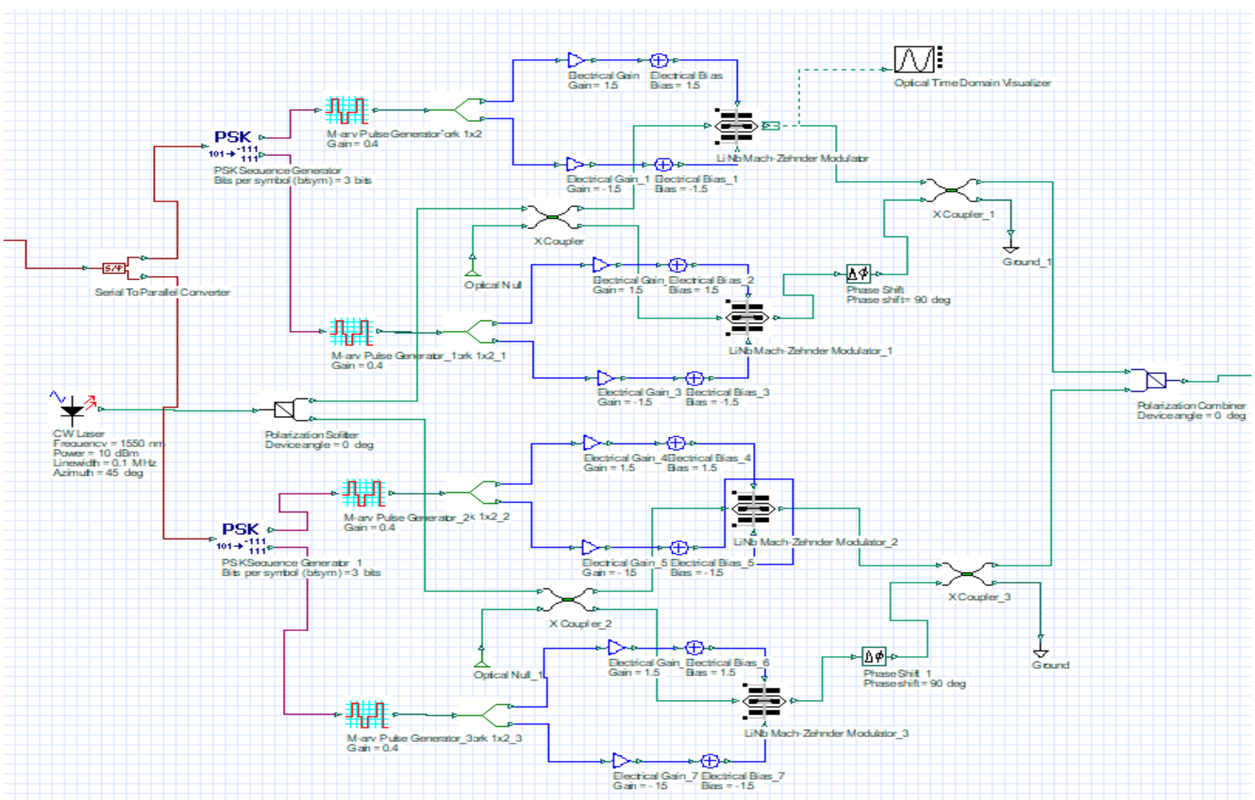


Figure 3.10 DP-QPSK modulator.

The pseudo random bit sequence (PRBS) generator is modulated by two QPSK modulators into two orthogonally polarized QPSK optical signals. PSK Sequence Generator is used in QPSK Modulator to Generate two parallel M-ary pulse generator sequences from binary signals as shown in figure 3.10. After signal passes through M-ary pulse generator it is modulated using Mach-Zehnder modulator and is combined together to form the single QPSK modulator. The vertical and horizontal polarization combined to make DP-QPSK modulator as shown in figure 3.10.

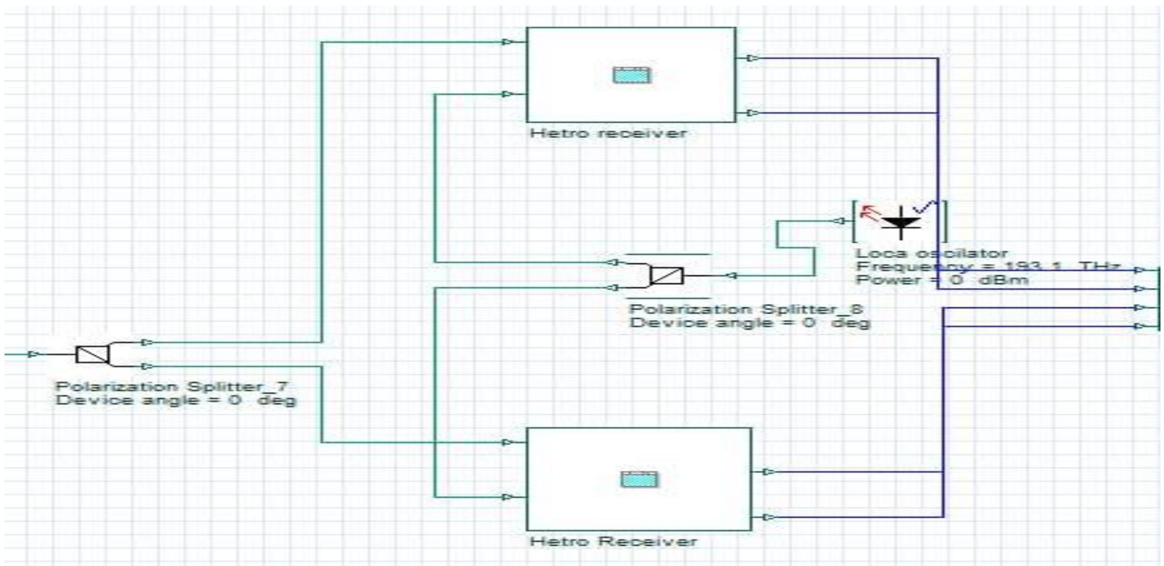


Figure 3.11 Heterodyne QPSK Receiver

After WDM-De-mux heterodyne DP-QPSK Receiver of I and Q of the two polarizations (X, Y), which have information signal. Receiver X has output X-I, X-Q and receiver Y has output of Y-I, Y-Q receive information per wave length as shown in figure 3.11. These Received signals are passed through Low Pass Gaussian filters after amplification. The heterodyne receiver QPSK receiver is design in which the incoming modulated RF signal is mixed with a local oscillator (LO) signal to produce an intermediate frequency (IF) as shown in figure 3.11.

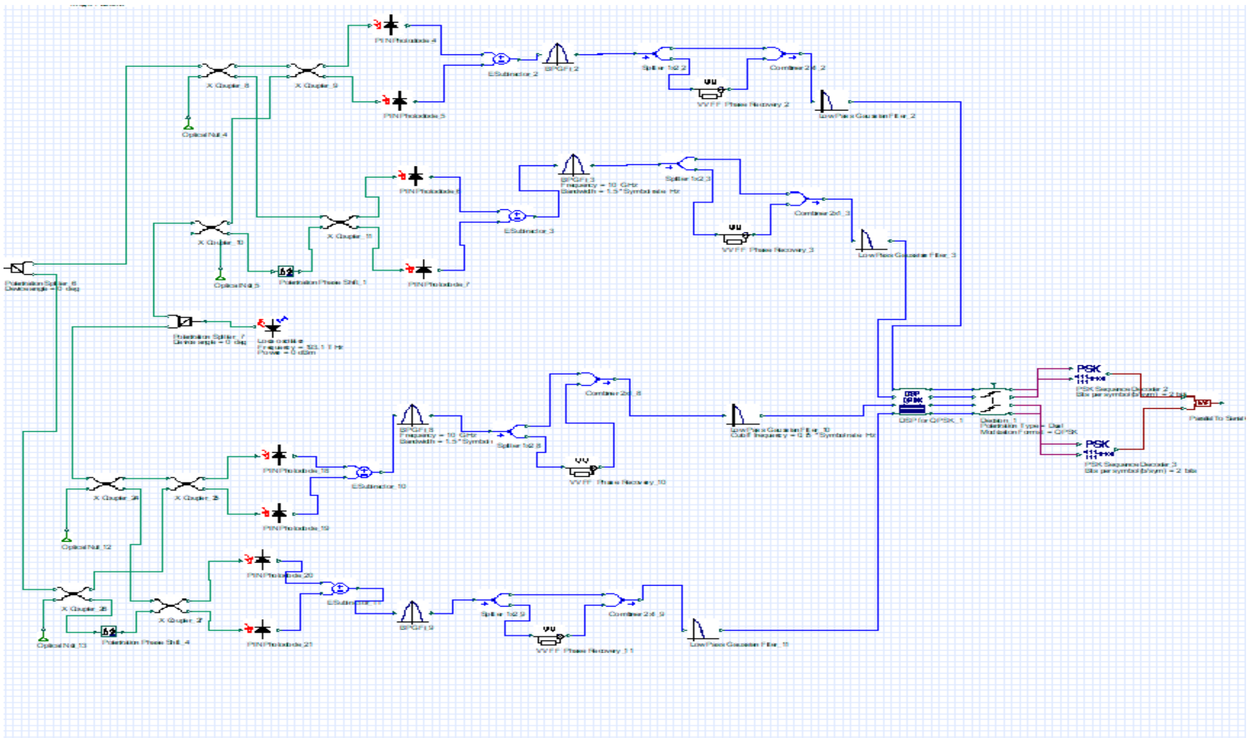


Figure 3.12 Heterodyne receiver

The carrier signal received is mixed with local oscillator and intermediate frequency is produced after mixing. The band pass filter isolate from intermediate frequency the frequency which is nearest to carrier frequency. After band pass filter carrier recover align the intermediate frequency in phase of initially modulated signal and finally passed through low pass filter to retrieve transmitted information as shown in figure 3.12.

Digital Signal Processing (DSP) is a key factor in improving the performance of DP-QPSK (Dual Polarization-Quadrature Phase Shift Keying). Main point how DSP enhancing the performance of DP-QPSK technology is discussed:

- ✓ **Dispersion Compensation:** Different wavelengths in optical fibers move at different rates, which causes chromatic dispersion and DSP algorithms can modify the phase and amplitude of received signals to correct for dispersion.
- ✓ **Polarization reuse**: DP-QPSK transmits separate data streams by using dual polarization, both horizontal and vertical. By reusing polarization solutions, DSP Optimize polarization alignment, signal quality and enhances overall system performance.
- ✓ **Phase Estimation:** In order to account for phase noise and other limitations, DSP algorithms estimate and track the phase to ensures reliable data recovery.

Following the completion of digital signal processing, the signal is sent to the detector and decoder as shown in figure 3.13. After processing the I and Q electrical signal channels that were obtained from the DSP stage, the Decision component normalizes each channel's electrical amplitudes to PSK.

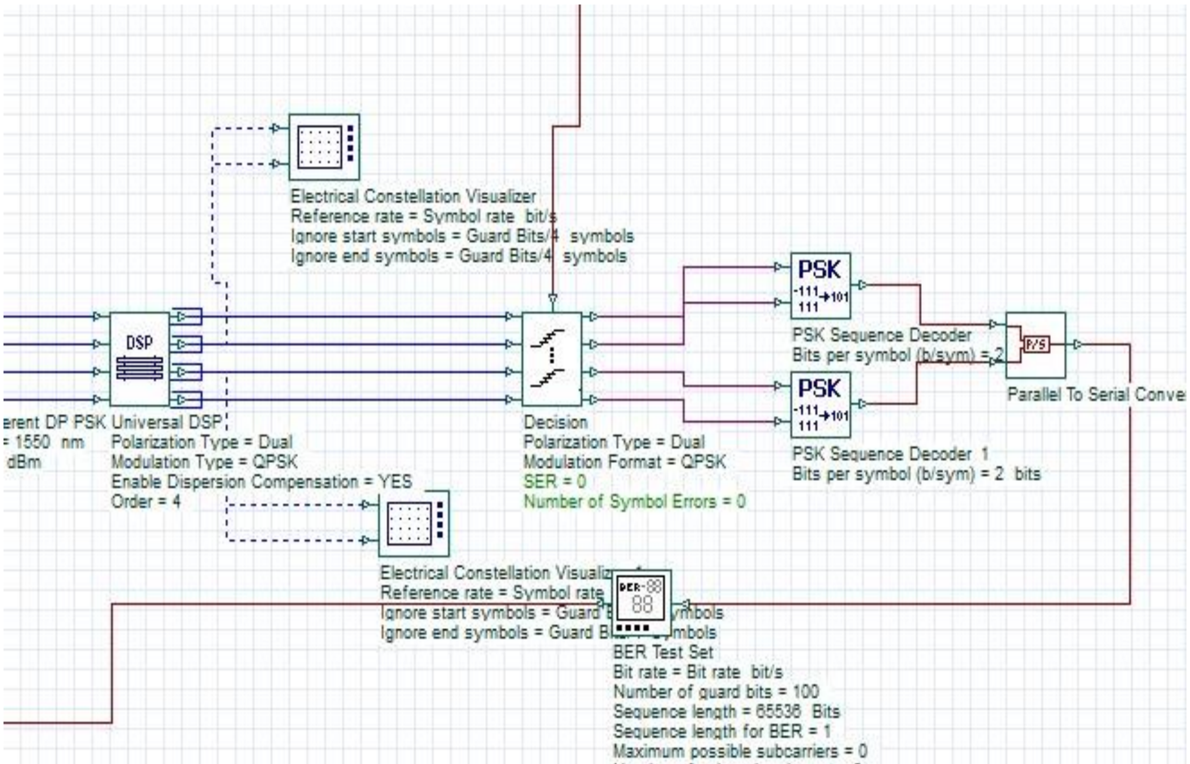


Figure 3.13 Detection and Decoder After DSP

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Introduction

This chapter presents the simulation and analysis of the system model. The results for each model design are obtained and analyzed using OptiSystem simulation software. Considering that the values of BER, Symbol Error Rate(SER), Error Vector Magnitude(EVM), Q-factor and constellation diagram, the performance of DP-QPSK for 100Gbps, 120Gbps and 140 Gbps data rate is analyzed under different fiber length. The reason for selection of DP-QPSK by evaluating with other PSK modulation such as 8-psk and 16PSK is also discussed. The downlink spectrum Analyzer of QPSK and 8-PSK and 16-PSK is also discussed. The parameter used in the simulation is listed in table 4.1.

Table 4.1 parameter used in simulation

Description	parameter	value
layout for DP QPSK for 100Gbps	bitrate	100Gbps
	symbol rate	25x109symbols/s
	sample per bit	4
	Guard Bits	100
	Reference wavelength	1550nm
Type of Modulation	DP QPSK	
	8-PSK	
	16-PSK	
Bitrate (Gbps)		100Gbps,120Gbps,140Gbps
Symbol Rate (Gbps)	Qpsk	Bitrate/4
	8-PSK	Bitrate/6
	16-PSK	Bitrate/8
Fiber Length	lengh	100km,120km,140km,160km,180km,200km
	attenuation	0.2/km
	Reference wavelength	1550nm
Input power	Q-PSK	1mw
	8-PSK	1mw
	16-PSK	1mw

Description	parameter	value
WDM Mux	Channel	4
	Bandwidth	(100, 120, 140)Gbps
	Insertion loss	0
	Filter Type	Gaussian
	other parameter	Default
WDM De-Mux	Channel	4(1550,1550.8,1551.6,1552.4)
	Bandwidth	(100, 120, 140) Gbps
	Insertion loss	0
	Filter Type	Gaussian
	other parameter	Default
DP-QPSK transmitter	Wavelength	1550nm,1550.8nm,1551.6nm,1552.4nm
DP-QPSK Receiver	wavelength	1550nm,1550.8nm,1551.6nm,1552.4nm
Gaussian Optical filter	Bandwidth	80Gbps for 100Gbps
	Insertion loss	0
	Wavelength	Four different wavelength in nm
DSP for QPSK	polarization	Dual
	channel wavelength	Four different wavelength in nm
	Reference Wavelength	1550nm
	propagation length	100km,120km,140km,160km,180km,200km
PSK Sequence Decoder	Bit/symbol/QPSK	2
	Bit/symbol/8-PSK	3
	Bit/symbol/16-PSK	4
Booster	Gain	20db
	noise figure	4db
Pre-Amplifier	Gain	20db
	noise figure	4db
PIN Photodetector	Responsivity	1A/W
	Dark Current	10nA

4.2.Performance Analysis of BER for Different Modulation Under Different Length.

The BER performance of QPSK, 8-PSK and 16-PSK is evaluated under bitrate of 100Gbps for different fiber length. As we have seen from figure of 4.1 as the fiber length increase the average BER of each modulation schemes increase. For 100Gbps the average BER over 100km fiber length for QPSK, 8-PSK, 16-PSK is 0.000103312, 0.000176013 and 0.001006336 respectively. The simulation result of OptiSystem for different modulation schemes under different length is listed in table 4.2. As we have seen from figure 4.2, QPSK exhibits the lowest BER as compared with 8-PSK and 16-PSK because of its simpler constellation and larger symbol spacing, while 8-PSK and 16-PSK have relatively higher BER due to their closer symbol spacing within the constellation.

Table 4.2 Simulation result of average BER for different modulation under different length.

Fiber length	BER(QPSK)	BER(8-PSK)	BER(16-PSK)
100	0.000103312	0.000176013	0.001006336
120	0.000172187	0.002486761	0.016879347
140	0.000252541	0.029953777	0.098462027
160	0.000359679	0.10824048	0.478322671
180	0.000417075	0.399889035	0.750027167
200	0.001817528	0.429988138	0.890058161

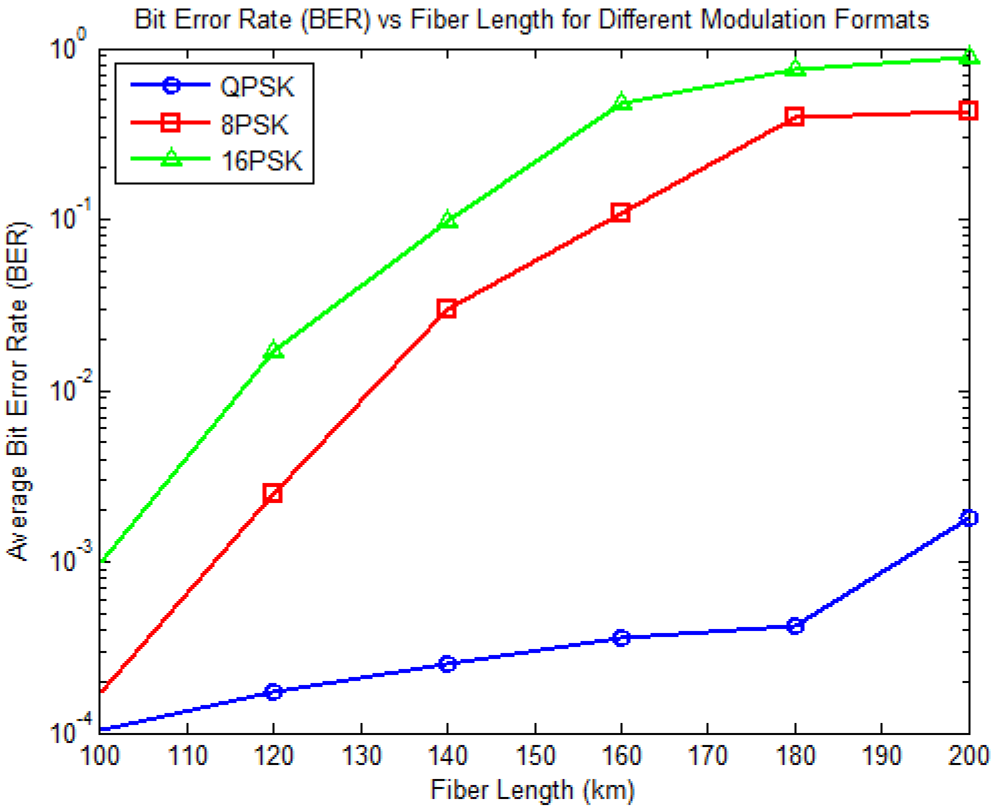


Figure 4.1 Average BER of different modulation for different fiber length.

4.3.Performance Analysis of Error Vector Magnitude (EVM) for Different Modulation Under Different Fiber Length.

In figure 4.2 the performance of QPSK, 8-PSK and 16-PSK is evaluated under bitrate of 100Gbps for different fiber length. As we have seen from figure of 4.2 as the fiber length increase the average EVM% of each modulation schemes increase. For 100Gbps the average EVM% over 100km fiber length for QPSK, 8-PSK, 16-PSK is 5.124994404, 6.796832463 and 8.017210126 respectively. The simulation result of OptiSystem for different modulation schemes under different length is listed in table 4.3. QPSK encodes 2 bits per symbol, 8PSK encodes 3 bits per symbol and 16PSK encodes 4 bits per symbol. Typically, QPSK exhibits the lowest EVM among the three because of its simpler constellation and larger symbol spacing, while 8-PSK and 16-PSK have relatively higher EVMs due to their closer symbol spacing within the constellation.

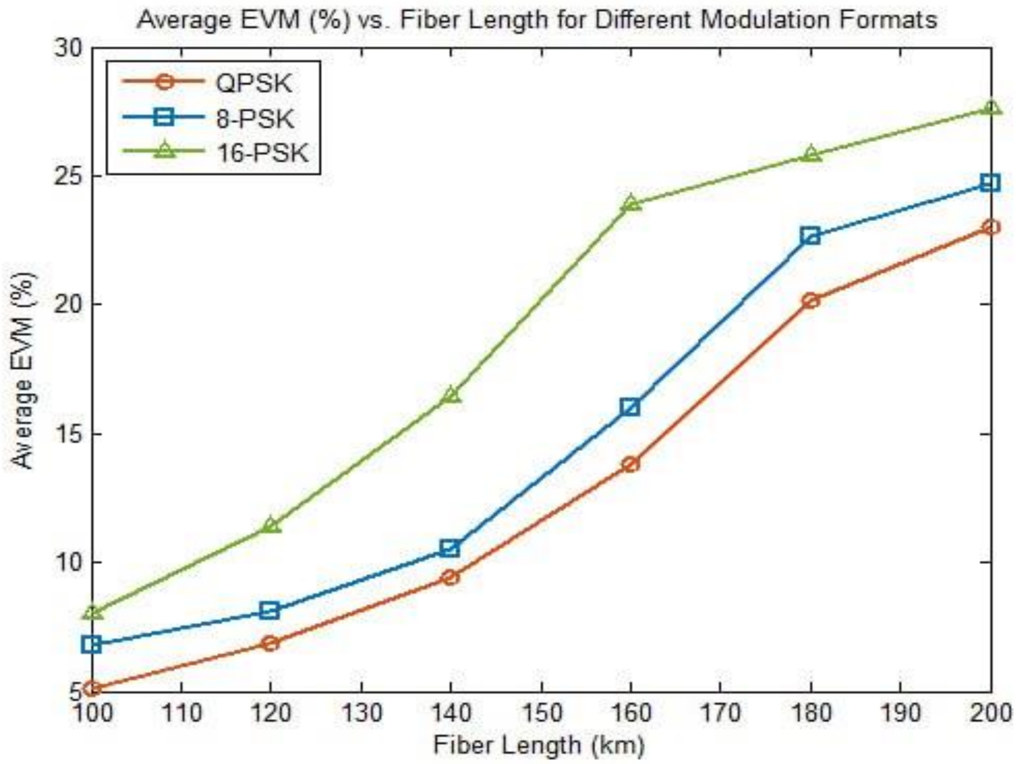


Figure 4.2 Average EVM of different modulation for different fiber length

Table 4.3 Simulation Data of Average EVM% for Different Modulation Under Different

length	EVM%(QPSK)	EVM%(8-PSK)	EVM%(16-PSK)
100	5.124994404	6.796832463	8.017210126
120	6.886673199	8.112617985	11.4110761
140	9.411725667	10.5442327	16.46086511
160	13.79812663	16.0207328	23.92002125
180	20.17771386	22.62374192	25.76791624
200	23.04254727	24.70346135	27.65690287

4.4. Performance Analysis of Symbol Error Rate (SER) for Different Modulation Under Different Fiber Length.

The SER of each modulation increase as fiber length increase, for over 100km the average SER achieved by QPSK, 8-PSK and 16-PSK is 0.000153055, 0.000516529 and 0.002056807 respectively for 100Gbps. The simulation result of different modulation schemes over different length at 100Gbps is listed in table 4.4. QPSK, with its four distinct symbols, is less susceptible to errors because of the greater phase separation between symbols, but 8-psk and 16-psk is more susceptive to error due to closer symbol spacing. at the length increase the SER increase for all modulation but stay low when contrasted with 8-PSK and 16-PSK as shown in figure 4.3.

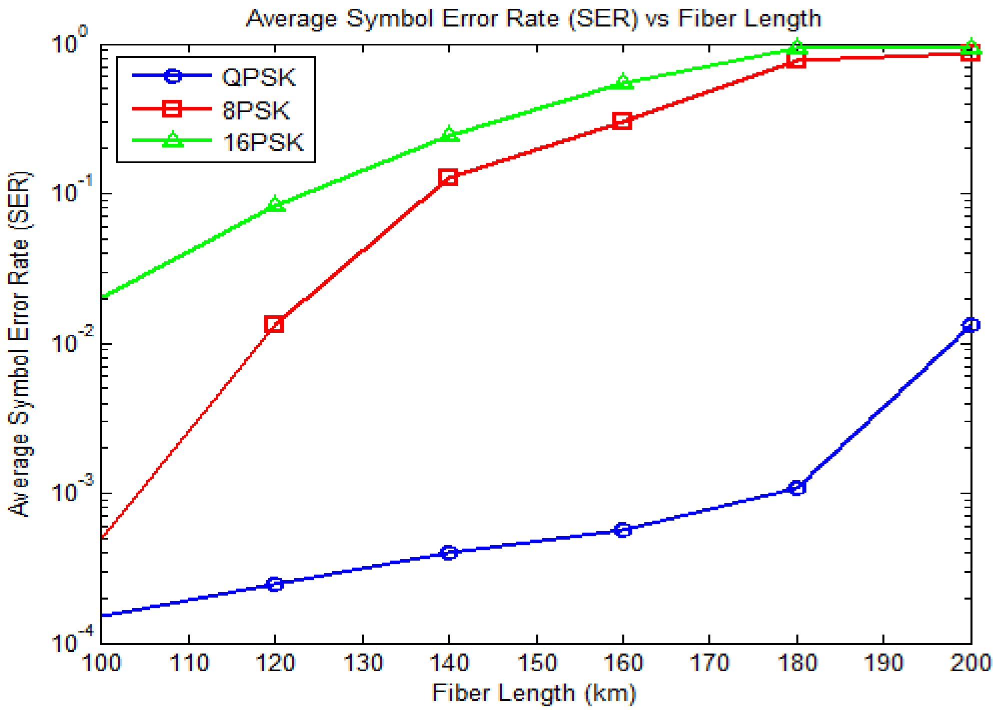


Figure 4.3 Average Symbol error rate for different modulation

Table 4.4 Average symbol error rate for different modulation under different length.

Fiber length	SER(QPSK)	SER(8-PSK)	SER(16-PSK)
100	0.000153055	0.000516529	0.002056807
120	0.000244888	0.013268242	0.082874632
140	0.000397681	0.128654461	0.2457762
160	0.000566254	0.30350551	0.548237023
180	0.001094343	0.767309458	0.923245593
200	0.013248745	0.867183196	0.931500979

4.5. Performance Analysis of Quality Factor for Different Fiber Length Under 100Gbps, 120Gbps, 140Gbps Bitrate for DP-QPSK.

Analyzing the Quality factor (Q-factor) performance across various fiber lengths at data rates of 100Gbps, 120Gbps, and 140Gbps using DP-QPSK modulation is crucial for understanding the limitations of high-speed optical communication systems. The key findings are as follows: The analysis indicates that while DP-QPSK is a dependable modulation scheme for high-speed optical communications, its Q-factor performance is significantly influenced by both fiber length and data rate. The system performs better at 100Gbps, showing greater Q-factors of 21.2 at 100km and over a range of fiber lengths, the Q-factor decreasing with increasing fiber length and at 200km the Q-factor is 3.11. As the data rate increases to 120Gbps and 140Gbps, the system becomes more susceptible to noise, which results in lower Q-factors, particularly at long distances as Figure 4.4 shows. The OptiSystem simulation result of different bitrate and different length is listed in table 4.5.

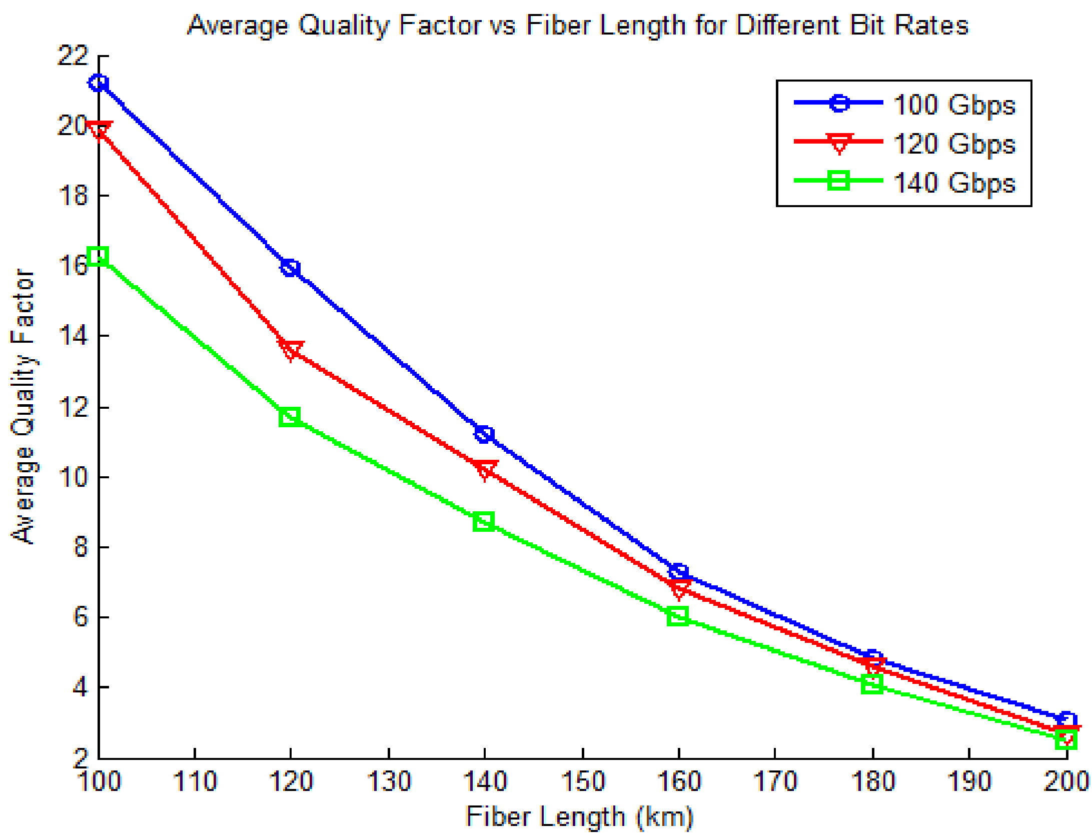


Figure 4.4 Quality factor versus fiber length

Table 4.5 Quality Factor of different bitrate at different fiber length.

Length	Q-Factor(100Gbps)	Q-Factor(120Gbps)	Q-Factor(140Gbps)
100	21.2	19.87	16.22
120	15.96	13.63	11.66
140	11.2	10.19	8.68
160	7.3	6.82	6.02
180	4.86	4.6	4.06
200	3.11	2.7	2.5

4.6. Performance Analysis of BER for Different Fiber Length Under Different Bitrate for DP-QPSK.

The data rate and fiber length have a major impact on Bit Error Rate (BER) performance.

At a data rate of 100Gbps, the QPSK exhibits relatively good performance and achieving the lowest BER of 0.000103312 at 100km and as the fiber length increase to 200km, BER is 0.001817528 for 100Gbps. The simulation result of different bitrate at different fiber length for QPSK modulation scheme is listed in table 4.6. The BER is increased across the evaluated fiber lengths. However, as the data rates rise to 120Gbps and 140Gbps, the system becomes more susceptible to noise, leading to increased BERs, especially over extended distances as shown in figure 4.5.

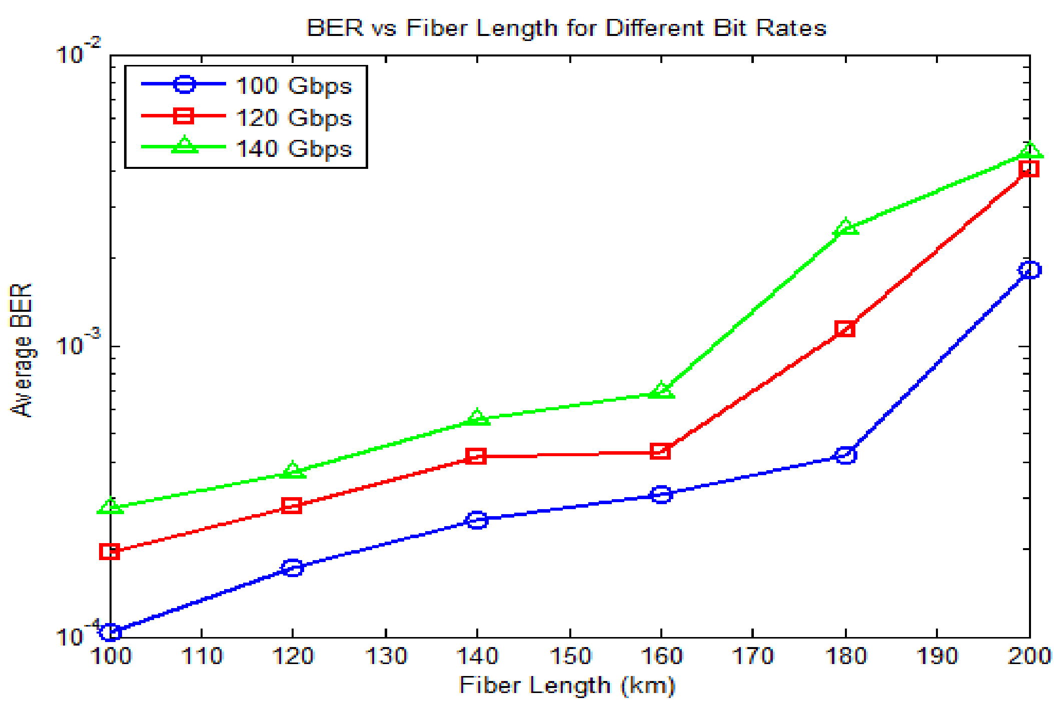


Figure 4.5 Average Bit Error Rate for Different Bit Rate at Different Fiber Length

Table 4.6 Bit Error Rate (BER) of Different Bit at Different Fiber Length.

Fiber length	BER(100Gbps)	BER(120Gbps)	BER(140Gbps)
100	0.000103312	0.000195145	0.000275499
120	0.000172187	0.000279325	0.000367332
140	0.000252541	0.00044539	0.000459165
160	0.000359679	0.00043238	0.000589262
180	0.000417075	0.00114026	0.000749969
200	0.001817528	0.00402152	0.007610659

4.7. Performance Analysis of Symbol Error Rate(SER) for Different Fiber Length Under Different Data Rate for DP-QPSK.

The study examines how different fiber lengths (100 km, 120 km, 140 km, 160 km,180km and 200 km) affect the Symbol Error Rate (SER) at data rates of 100Gbps, 120Gbps, and 140Gbps, utilizing Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK) modulation. It reveals the correlation between fiber length, data rate, and SER. As the length of the fiber increases, the Symbol Error Rate (SER) also increases for all data rates as shown in figure 4.6, owing to factors like attenuation, chromatic dispersion, and nonlinear effects. At fiber length of 100km and 100Gbps the SER is 0.000153055 and as data rate is increased to 140Gbps at 100km the SER is increased to 0.000352026. The simulation result of each data rate at different fiber length is listed in table 4.7. The SER is increased at higher data rates, such as 120 Gbps and 140 Gbps and its more prone to performance degradation over longer distances compared to 100 Gbps. This is due to their higher bandwidth demands and increased sensitivity to noise and nonlinear effects.

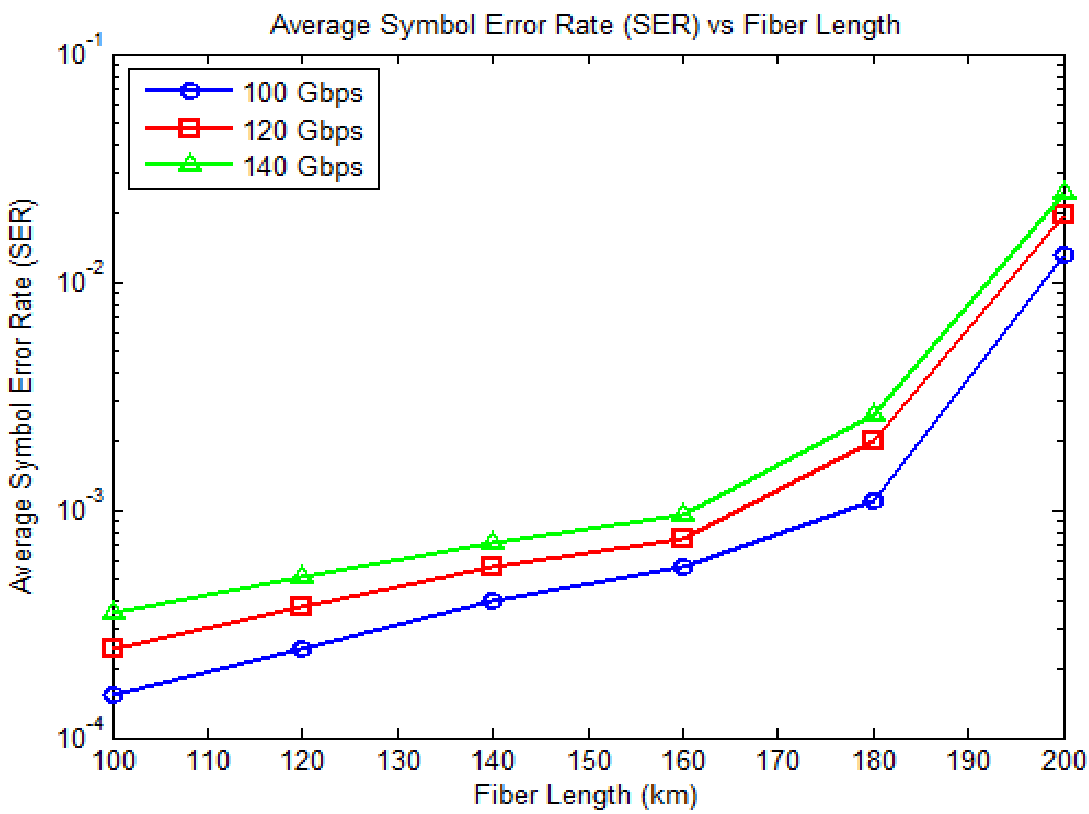


Figure 4.6 Average Symbol Error Rate for Different Bitrate at Different Fiber Length.

Table 4.7 Average Symbol Error Rate for Different Bits and Fiber Length.

Fiber Length	SER(100gbps)	SER(120Gbps)	SER(140Gbps)
100	0.000153055	0.000244888	0.000352026
120	0.000244888	0.000374985	0.000505081
140	0.000397681	0.000566254	0.000719359
160	0.000566254	0.000742317	0.000956594
180	0.001094343	0.001997368	0.002632546
200	0.013248745	0.013248745	0.024584492

4.8. Performance Analysis of Error Vector Magnitude(EVM) for Different Fiber Length Under Different Bitrate for DP-QPSK.

In the performance analysis of error vector magnitude for dual polarization for DP-QPSK modulation, a distinct trend of increasing EVM is noted with both growing fiber length and bit rate as shown in figure 4.7. This indicate that as the fiber transmission distance extends, issues such as chromatic dispersion and fiber non-linearity build up, leading to signal degradation. Higher bitrate (120Gbps and 140 Gbps) exhibit high EVM value at each fiber length compared to 100Gbps bitrate. At bitrate of 100Gbps and fiber length of 100km the average EVM% is 5.124994404 as the fiber length increased to 200km at 100Gbps the average EVM% is increased to 23.04254727. The simulation result of different bitrate at different fiber length is listed in table 4.8. Since higher data rates cause more signal distortion due to their increased bandwidth usage and higher susceptibility to noise and dispersion effect.

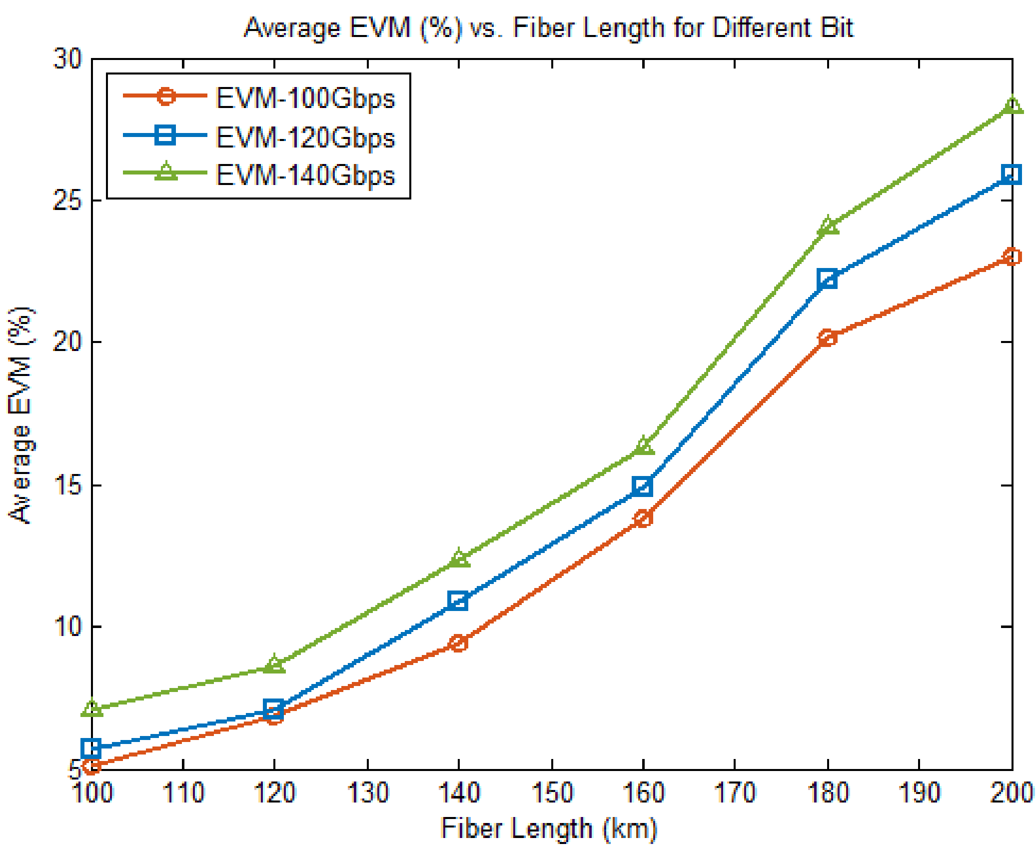


Figure 4.7 Average error vector magnitude for different bit rate at different fiber length.

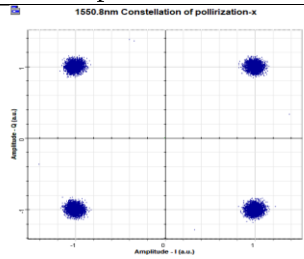
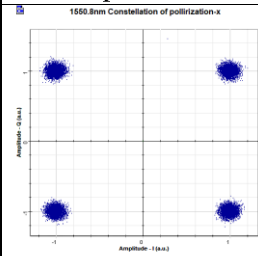
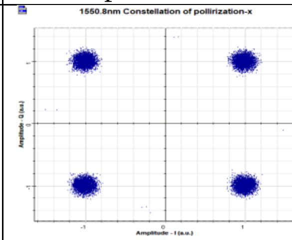
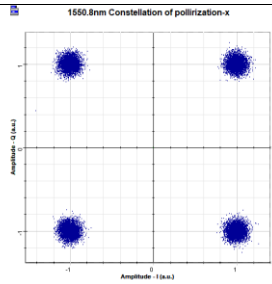
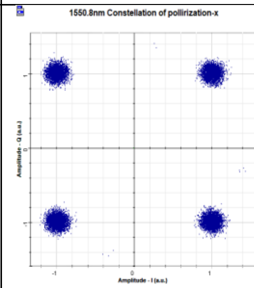
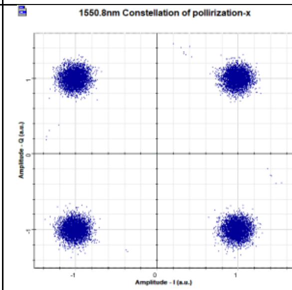
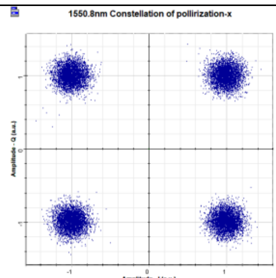
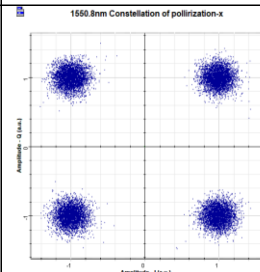
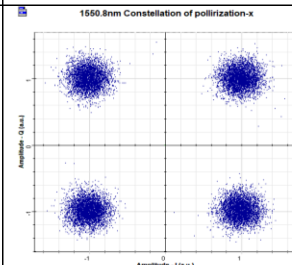
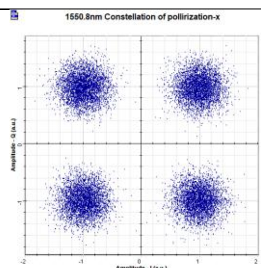
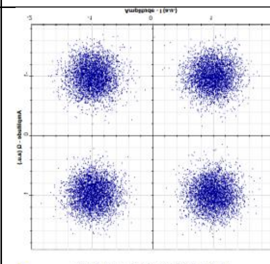
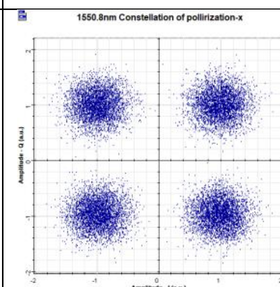
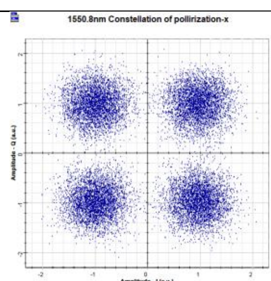
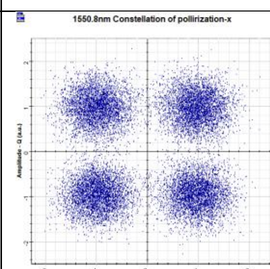
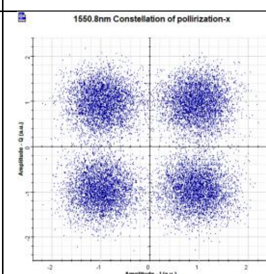
Table 4.8 Average EVM% of Different Bitrate at Different Fiber Length.

length	EVM%(100Gbps)	EVM%120Gbps	EVM%140Gbps
100	5.124994404	5.663130588	7.116120609
120	6.886673199	7.117734222	8.620971071
140	9.411725667	10.91443841	12.32911848
160	13.79812663	14.88666875	16.32738997
180	20.17771386	22.23088773	24.04048109
200	23.04254727	25.896397	28.26278878

4.9. Performance Analysis of Constellation Diagram for Different Fiber Length Under Different Bitrate for DP-QPSK.

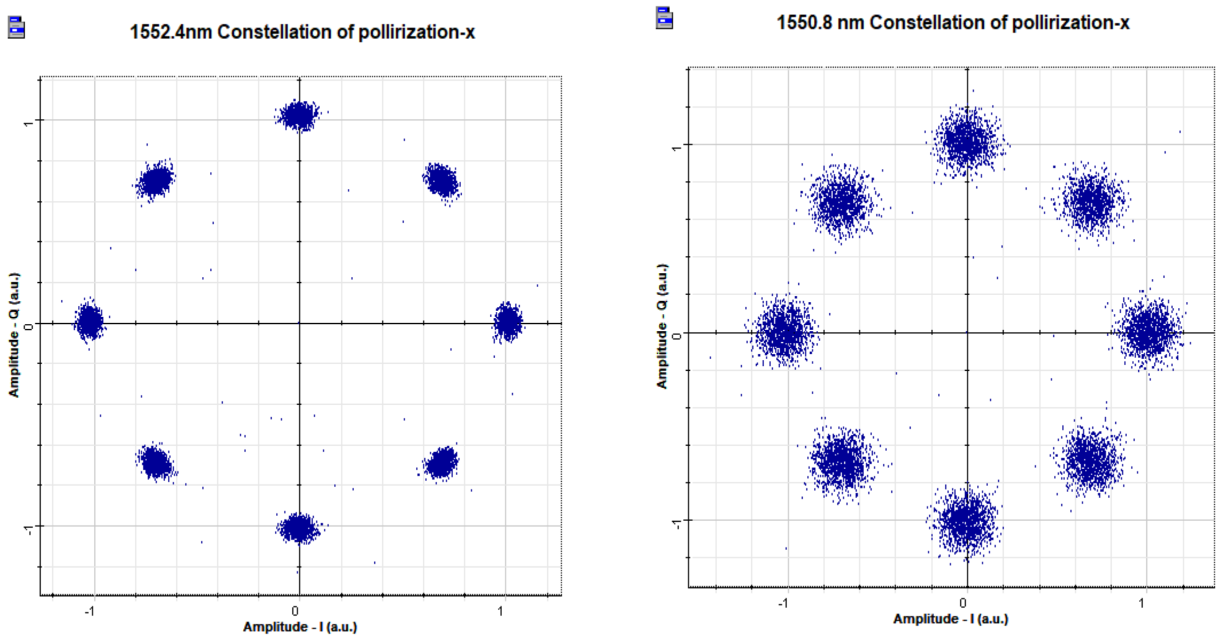
Constellation diagrams are vital in optical communication, serving as tools to visualize the quality of the transmitted signal. From OptiSystem simulation analysis, with the increase in fiber length and bitrate, signal attenuation and dispersion lead to the spreading and blurring of constellation points, resulting in elevated symbol error rates. The constellation diagram of different bitrate at different fiber length is analyzed in table 4.9. The constellation diagram is influenced by distortion as the modulation order increase. The higher order like 16 PSK contain 4 bit per symbol and as the number of symbol point is increase the spreading of constellation point followed with influence of cable length and bitrate.

Table 4.9 constellation diagram of different bitrate at different Fiber length.

Length of Fiber	100Gbps	120Gbps	140Gbps
100km			
120km			
140km			
180km			
200km			

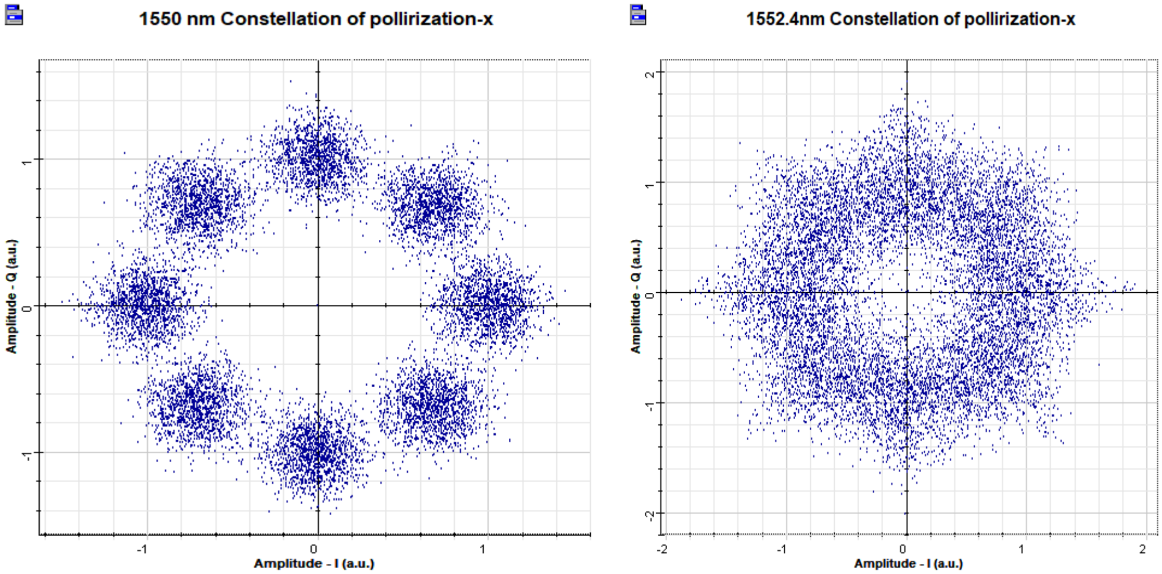
4.10. Performance Analysis of Constellation Diagram for Different Fiber Length and Bitrate of 100Gbps for 8-PSK

The constellation point of 8-psk evaluated shown in figure 4.8 and 4.9 over a fiber length of (100,120,140,160) km and as distance of fiber increase the constellation point become away from ideal position. During this time the symbol error rate and bit error rate increase and the signal quality become low. In figure 4.8(a) the symbol is condensed in ideal position and as distance increase the point become spread over the plane as shown in figure 4.8(b), as the fiber length increase to 120km as shown in figure 4.9 (a) the movement of constellation point increase and at 160km the constellation point is spread and become shapeless as shown in figure 4.9(b).



(a) (b)

Figure 4.8 Constelletion diagram 8-psk for 100Gbps under (a) 100km (b) 120km

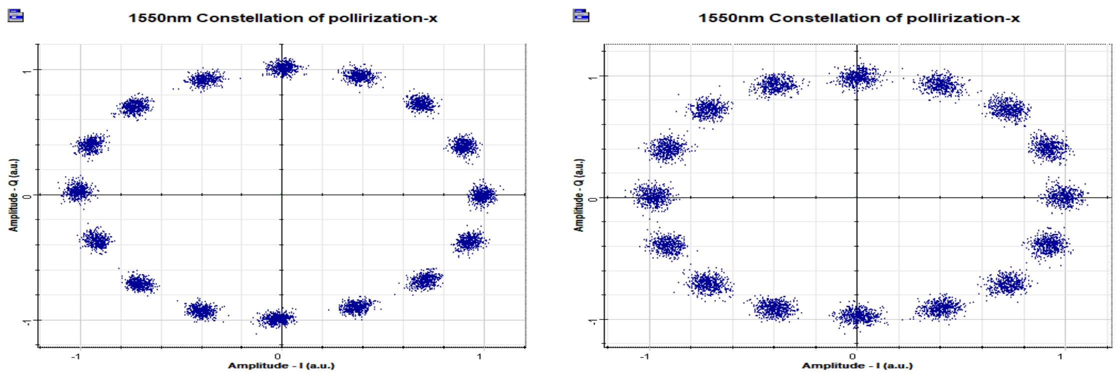


(a) (b)

Figure 4.9 Constelletion diagram 8-psk for 100Gbps under (a) 140km (b) 160km

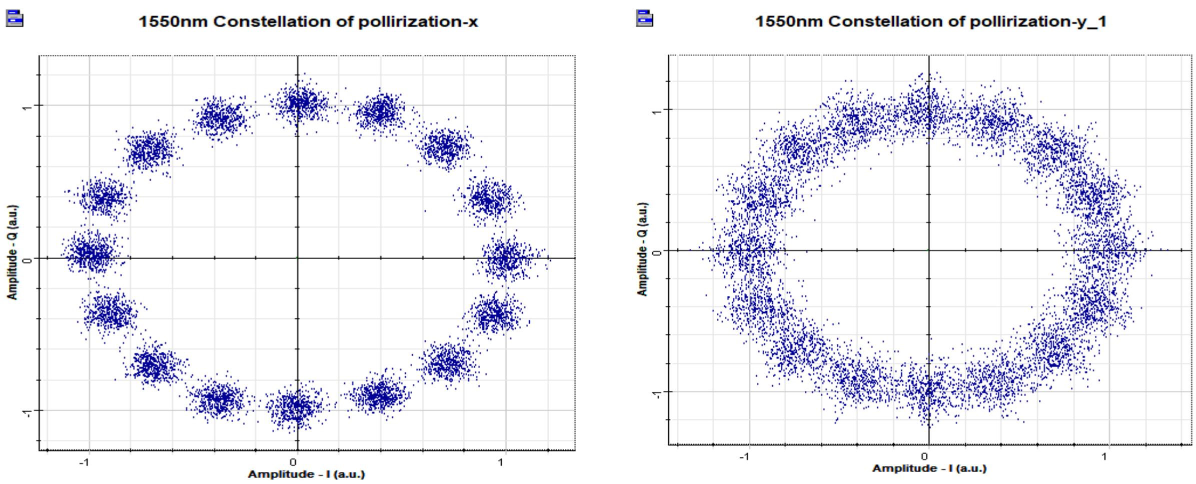
4.11. Performance Analysis of Constellation Diagram for Different Fiber Length Under Different Fiber Length for 16-PSK

The evaluation of constellation point of 16-psk over a fiber length of (100,120,140,160) km are discussed and as distance of fiber increase the constellation point become depart from ideal position. As the departing of constellation point increase the symbol interference occur and errors become dominant. At 100km as shown in figure 4.10(a) the symbol is condensed at ideal position and as distance increase to 120km the point become spread over the plane as shown in figure 4.10(b) as the fiber length increase to 140km as shown in figure 4.11 (a) the movement of constellation point increase and at 160km the constellation point is spread and become shapeless as shown in figure 4.11(b).



(a) (b)

Figure 4.10 Constellation diagram 16-psk for 100Gbps under (a) 100km (b) 120km

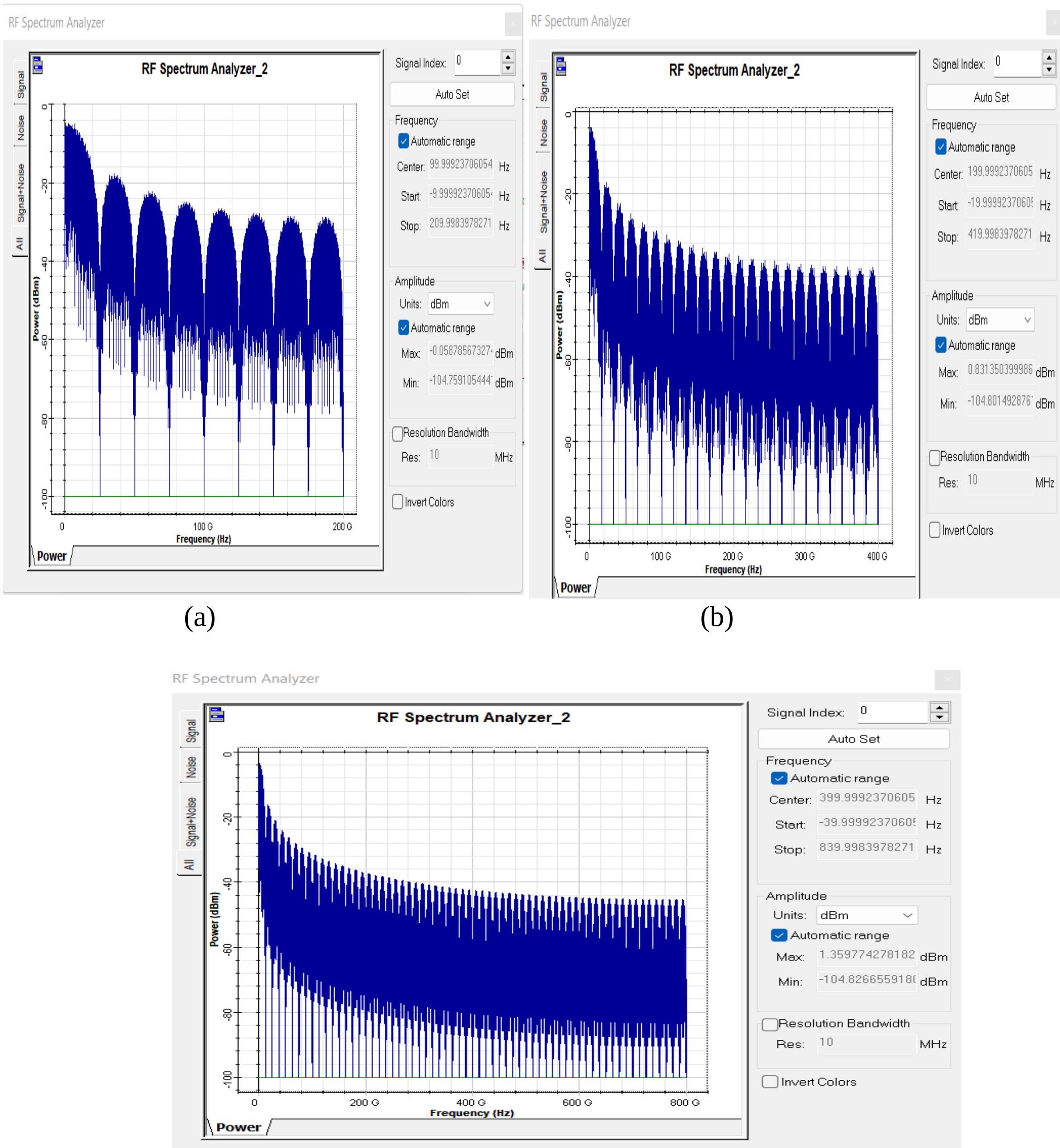


(a) (b)

Figure 4.11 Constelletion diagram 16-psk for 100Gbps under (a) 140km (b) 160km

4.12. Performance Analysis of Different Modulation Spectrum Analyzer.

Spectrum efficiency is the rate of information transfer per unit bandwidth and it measures how effectively a given modulation scheme utilizes the available bandwidth. QPSK transmit 2 bit per symbol, 8-PSK transmit 3 bit per symbol and 16-PSK transmit 4 bit per symbol. QPSK Uses more bandwidth compared to 8-PSK and 16-PSK for the same data rate. 16-PSK requiring the least bandwidth for the same data rate compared to the QPSK and 8-PSK and have highest spectrum efficiency compared with QPSK and 8-PSK.



(a) (b)

(c)

Figure 4.12 Spectrum analyser of (a) QPSK (b) 8-PSK (c) 16-PSK

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1. Conclusions

This thesis investigated the design and performance analysis of a Wavelength Division Multiplexing Passive Optical Network (WDM PON) utilizing a heterodyne receiver. It focused mainly on QPSK modulation schemes and compare the of performance with 8-PSK, and 16-PSK modulation schemes. The simulation was conducted using OptiSystem Version 20 software. By using different bitrate of 100Gbps,120Gbps and 140 Gbps the performance QPSK is analyzed and discussed. The BER, SER, EVM, Quality factor and constellation diagram parameter is used to analyze the performance of QPSK under different fiber length. The QPSK with 4 symbol has less bit error rate, symbol error rate, error vector rate and high quality factor as compared with 8-psk and 16-psk for different value of bitrate and fiber length. The constellation diagram is not distorted as fast as that of 8-psk and 16-psk because of greater phase separation between symbols.

As the distance between transmitters and receiver's increases, the Q factor decreases at 200 km, it reads a Q-factor of 3.11 at 100Gbps. This indicates that the constellation diagram become blur and the signal become distorted. In contrast, at a fiber length of 100km, the value of the Q factor is increased to 21.2, which indicates the constellation diagram become closely condensed. The relationship between fiber length and Q factor is inversely proportional, which means as fiber length increases, the quality factor decrease and at low fiber length we get a good Q factor. The error vector magnitude measure how the symbol is departing from proper position in constellation diagram and high EVM means the symbol is departed from proper position and the value become high, small EVM means that the symbol is nearest to proper position or very close to the position and the distance become very less and the value of EVM is small. From this study it is analyzed that as the distance and bitrate increase the value of EVM increase due to noise, non-linearity and dispersion. The value of symbol error rate is also affected by distance and bitrate as further investigated in the study. As the distance increase the value of SER is decrease because the transmitted symbol is affected further by dispersion due to inter symbol interference and signal attenuation

5.2. Recommendation

WDM PON technology is the promising technology for modern communication system to deliver high speed low latency 5G service. The PON Service is cost effective and resource managing service in which the current service is highly delivered. In this study WDM PON is specifically studied under QPSK, 8-PSK and 16-PSK modulation and heterodyne Receiver. We recommend the evaluation of PON under hybrid WDM and TDM using higher order modulation like 128QAM and 256QAM for Further analysis and proposing how to minimize the latency occur due to dynamic bandwidth allocation of TDM.

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