Design of Wavelength Division Multiplexing based Passive Optical Network Transmission System using Heterodyne Receiver for 5G Transport

MASTERS OF SCIENCE IN COMMUNICATION ENGINERRING AND NETWORKING

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A THESIS SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN COMMUNICATION ENGINEERING AND NETWORKING

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I hereby declare that this MSc thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

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Abstract

Fifth Generation network standard has put higher peak data rate (10x) and very low latency requirements (1/10) as compared to its predecessor 4G network. In any mobile network implementation, the transport network is critical component for delivering the intended services. The demand for high data rate in 5G requires massive capacity upgrade in the transport network. On the other hand, latency in 4G and older technologies is too much as compared to 5G requirements. Hence Building low-latency and high-capacity transport networks is vital for new high-speed cellular technologies. Optical fiber-based technologies are essential to meet the high bandwidth demands of 5G transport Network. The two contending optical technologies for 5G transport are point-to-point (P2P) fiber access and point-to-multipoint (P2MP). P2P fiber access has low fiber efficiency and requires infrastructure installation for new deployment. Point-to-multipoint fiber has high fiber efficiency as compared to P2P. Among the P2MP fiber options, TDM-PON uses dynamic bandwidth allocation (DBA) to multiplex services which introduces 1ms delay. On the other hand, WDM-PON doesn't require DBA, thus is a good candidate for low latency services. Studies on WDM-PON are using homodyne receiver. The proposed network was simulated in Opti Wave Optisystem simulation software. In this thesis, a new 2.4 Tbps WDM-PON based network using heterodyne receivers was built as solution for 5G transport network requirements. The performance of the new system was compared with back-to-back model using BER and OSNR. An OSNR of 15.4 is required to obtain a BER of 10^{-3} dB for Heterodyne System while an OSNR of 14.8 dB is required for Back-to-Back System which is 0.6 dB higher. The results obtained from the Heterodyne system simulation are very close to the result found in case of back-to-back system. Hence, the WDM Dual Polarization 8-PSK PON system with heterodyne receiver can be used in 5G transmission.

Keywords: Passive Optical Network (PON), Wavelength Division Multiplexing (WDM)

List of Abbreviations

AS	Autonomous System
ASK	Amplitude Shift Keying
BBU	Baseband Unit
BER	Bit Error Rate
C-RANs	Cloud-Radio Access Networks
CU	Central Unit
DBA	Dynamic Bandwidth Allocation
DP-QPSK	Dual-polarization Quadric Phase-shift keying
DSP	Digital Signal processing
DU	Distributed Unit
EDB	Electrical Duo-Binary
FH	Fronthaul
FSK	Frequency Shift keying
IEEE	Institute of Electrical and Electronics Engineers
ITU-R	International Telecommunication Union Radio
KPI	key performance index
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
OSNR	Optical Signal to Noise Ratio
PAM	Pulse Amplitude Modulation
PSK	Phase Shift Keying
P2P	Point-to-point
RU	Remote Unit
TDM-PON	Time Division multiplexing Passive Optical Network
WDM	Wavelength division multiplexing
4G	Fourth generation mobile network
5G	Fifth generation mobile network

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Chapter One

1 Introduction

1.1 Background

Increasing mobile traffic have been stimulating a continuous capacity expansion of wireless networks, and ITU-R announced the vision and key performance indexes (KPI) of 5G network such as over 10 Gbps throughput per cell, 1 Gbps guaranteed per user, and 1 ms latency [9]. Passive optical network (PON) technologies are attractive solution to support explosive mobile data traffics as well as to support residential and business services. The data rate per wavelength in PON is also evolving 10 Gb/s to 25 Gb/s, and NG-EPON defined by IEEE 802.3ca supports 25G and 50G-ONU coexistence structure in a single ODN. Therefore, the NG-EPON could be used to satisfy high capacity and low latency requirement of 5G services [2].

1.2 5G Transport Overview

In addition to faster speed and higher bandwidth as compared to 4G/LTE, 5G networks are designed to take advantage of cloud and virtualized network concepts and to support massive Machine type communications [3]. In order to solve the shortcomings of conventional RAN systems and provide support for services that need extremely low latency, high reliability, density, and mobility, cloud-radio access networks (C-RANs) have recently been put out as a key concept. In CRAN, the Baseband Unit (BBU) pool is placed in the Central Unit (CU), which is connected to the Remote Units (RUs) by high-bandwidth transport links that transmit I/Q streams, or fronthaul (FH) [11]. The Central Unit [CU] is usually installed in the central office, whereas the Distributed Unit [DU] is deployed at outside. The physical link between CU and DU, Fronthaul, is connected by optical fiber in the existing optical distributed network (ODN) [9]. The supporting of guaranteed bandwidth and low latency with cost-effective optical technologies is one of major issues in Fronthaul link to provide massive connectivity, low latency, and capacity enhancement in 5G wireless systems [9].

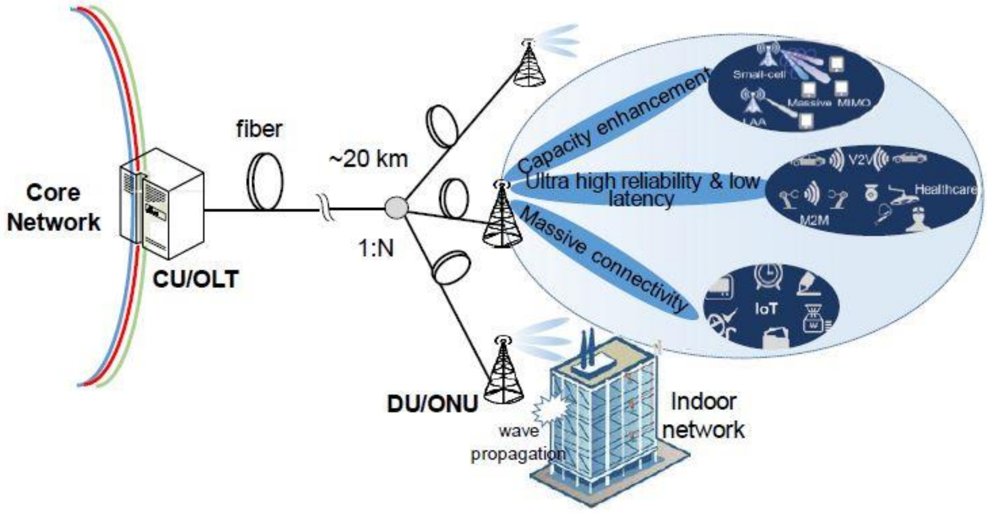


Figure 1-1 Optical access network for 5G mobile communication network

1.3 Optical Technologies for 5G Transport

In the long run, optical fiber-based solutions are necessary to meet the high bandwidth demands. Among the optical fiber technologies, the selection depends on each operator's deployment requirements and timeline. The two optical technologies that are in competition: PON and point-to-point (P2P) fiber access [3] are:

1.3.1 Point-to-Point fiber access

P2P fiber access is the most straightforward technique and has been widely deployed in fiber-rich areas. For distances typically shorter than 20 km, the current systems offer bi-directional transmission at 100 Mb/s and 1 Gb/s using either one or two fibres. Higher speed versions are under development. In a dedicated link, there is plenty of bandwidth available, and transmission distance is the main factor limiting latency. 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 [3].

1.3.2 Point-to-MultiPoint fiber access

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) in the central office, an optical distribution network (ODN) with passive power or wavelength splitters, and optical network units (ONUs) at the locations of the subscribers. For TDM-PON, a passive optical power splitter is used in the ODN. Each ONU burst broadcasts in the upstream direction at a designated time-slot, and the signals from all ONUs are multiplexed in the time domain. For WDM-PON, each ONU is assigned a specific wavelength. Either the ODN (using passive wavelength splitters) or the ONU itself can do the wavelength selectivity (by wavelength filters). TDM-PON employing traditional dynamic bandwidth allocation (DBA) Mechanism, which could take up to approximately 1 ms delay, is incompatible with the Fx interface requirements for delay-sensitive 5G services. On the other hand, WDM-PON does not require DBA, thus is a good candidate for low latency services [3].

1.4 Statement of the Problem

Among the requirements set by MT-2020 for 5G are, a peak data rate of 20 Gb/s each sector, 1 Gb/s user experienced data rate and 1ms latency. For a Macro cell, the total peak wireless data rate for a single sector is assumed to reach 60 Gb/s . In a macro cell the number of users exceeds 2000.Since the peak data rate of each user can reach 1Gbps, the total data rate reaches 2Tbps [2,4,29].

In the process of building a high-capacity mobile network such as 5G, one of the important issues is to select an efficient transport network. Optical Fiber based transport networks are proving efficient in this regard. Point-to-point and point-to-multi-point fiber access technologies are among the options for fiber-based transport, the latter being preferable since it has high fiber efficiency. P2MP fiber access systems widely use either TDM or WDM. WDM-PON doesn't need a DBA scheme, hence a good candidate for low latency services like 5G.

Except for short distance, the performances of homodyne and heterodyne receivers are roughly the same. On the other hand, when compared to homodyne receivers, heterodyne receivers are substantially simpler to implement i.e., Heterodyne detection simplifies the receiver design. [12,13,25].

Issues observed:

- ✓ 5G network deployment for macro cells need a data rate higher than of 2 Tbps.
- ✓ For Implementation transport networks, using heterodyne receivers is much easier than using heterodyne receivers.

The aim of this thesis work is, to present a 2.4 Tbps coherent WDM using PON with heterodyne receivers as solution for 5G transport and analyse performance to contribute its share in addressing the issues mentioned above.

1.5 Objective

1.5.1 General objective

The General objective of this thesis is to design a 2.4 Tbps Coherent WDM based PON Transmission system with heterodyne receivers which can satisfy 5G Transport requirements.

1.5.2 Specific Objective

- ✓ To identify Multiplexing and modulation techniques for Transmission System
- ✓ To model & simulate the system using identified methods using Optisystem software
- ✓ To Analyze the simulation result using constellation diagrams , Evaluate Bit Error (BER) and Optical Signal to Noise Ratio (OSNR) performance

1.6 Thesis Contribution

High bandwidth capacity and low latency/jitter requirements of 5G network standard in the front-haul & backhaul Transport are one of the challenging tasks in telecommunication Industry and key for successful implementation of the technology. This thesis work presents a high-speed (2.4 Tbps) coherent WDM using PON with heterodyne receivers to meet the 5G transport requirements.

1.7 Methodology

The methods employed to achieve the objectives of this thesis are:

Literature review: involves reading books, publications, simulation tools and other resources related to Wavelength Division Multiplexing Using Passive Optical Networks.

System Model: Modeling a 2.4 Tbps WDM-PON using heterodyne receiver transmission system to analyze its performance.

Simulation: System modeling and simulation would be carried out in Opti wave Optisystem

Result and Discussion: Finally, the results obtained from the simulation results analyzed and compared based on performance analysis criterions [BER, OSNR]

Chapter Two

2 Literature Review

There are different researches in the area of 5G-transport system based on WDM-PON. Some literature related to the work in this thesis are,

In[1] It reviewed evolving and future PON technologies for 5G transport systems and investigated coherent WDM-PON system employing DP-QPSK transceivers . A total transmission capacity of 1.6 Tbit/s (100 Gbit/s/λ × 16 wavelengths) was achieved using coherent DP-QPSK receiver, homodyne receiver design.

[2] Reviewed optical access and transport technologies for 5G and beyond, and introduced recent feasibility Demonstration of NG-EPON prototype supporting channel bonding and low-latency dynamic bandwidth allocation Technologies. It also showed that 50G-PON could support bandwidth-intensive as well as low-latency services for 5G mobile Network. 50Gb/s of data rate was a result of bonding two wavelengths.

[3] Reviewed key 5G wireless transport standards and discussed optical access technologies and standards development activities, and finally, highlighted several state-of-the-art PON technologies. A single-wavelength up to 50 Gb/s data rate was proposed using PAM-4, duo binary and DMT modulation techniques.

[4] Built a new scheme for coherent wavelength division multiplexing (WDM) with passive optical networks (PON) having capacity of 800 Gbps network. The scheme was simulated using dual-polarization quadric phase-shift keying (DP-QPSK) transceiver and homodyne receiver. It suggested network would continue to reach more than 1 Tbps in capacity for longer distances and an improvement on the network may be apply with replacing homodyne receiver with heterodyne one for reducing cost effect when interfacing to radio equipment.

[5] Modeled WDM-PON transmission system that is capable to providing data transmission of up to 32 Gbit/s per channel using forward error correction (FEC) and Fiber Bragg grating-based dispersion compensation module (FBG-DCM).

[6] Introduced the use of pre-chirping technique to WDM-PON and compared the achievable Performance of PAM-2, PAM-4 and EDB under demanding band limited and dispersive conditions on the transmission of 50 Gb/s using adaptive equalization, with and without pre-chirping. The reach of 50 Gb/s HS-PON per channel when using PAM-2 in O-band and PAM-4 in C-band was beyond 20Km.

[7] Provided an overview of the ongoing work supporting the specification of open interfaces between the different 5G building blocks. It also presented several technologies that can facilitate effective transport networks, described the architectural challenges in designing flexible 5G transport networks, and provided dimensioning guidelines.

[8] Reviewed recent progress of 100 Gb/s to 1 Tb/s class coherent PON technology and latest trends In coherent DSP. It also summarized the key successful factor for realizing 100 Gb/s to 1 Tb/s based coherent PON systems and a data rate of 800 Gb/s (100 Gb/s/λ x 8 wavelengths) based on WDM-PON was achieved.

[9] Discussed low-cost high-capacity optical front haul solutions enabled by advanced modulation formats and wavelength-agnostic passive wavelength division multiplexing (WDM) technology. It also reviewed the recent standardization effort on time-sensitive networking in support of 5G front haul and presented an FPGA-based implementation providing low latency and demonstrated with real-time, 25-Gb/s PON prototype based on Ethernet-PON MAC/PHY, O-band transmitter, and APD receivers. systems.

Paper	Method	Capacity	Receiver Design
[1]	DP-QPSK	100 Gbit/s/λ [16 wavelengths, 1.6 Tbit/s]	Homodyne
[3]	PAM-4	50 Gb/s/λ	Homodyne
[4]	DP-QPSK	100 Gbit/s/λ [8 wavelengths, 800 Gbps]	Homodyne
[8]	DP-QPSK	100 Gb/s/λ [8 wavelengths, 800 Gbps]	Homodyne

Table 2-1 Summary of Literature Review

Chapter Three

3 5G Network Architectures and Fiber Optic Communication Systems

Massive machine-type communications (mMTC), enhanced mobile broadband (eMBB), and ultra-reliable low-latency communications (URLLC) are the three generic services that 5G services are primarily intended to enable. Together, wireless and optical networks can provide a more seamless experience across fixed and mobile applications than either could individually in order to achieve these needs. The revolutionary objectives of 5G just could not be achieved without fiber [2] .

To address these challenges, several studies propose PON as 5G MFH/MBH architecture solution. Because it is enabling a flexible and software-defined reconfiguration of all networking elements in a multi-tenant and service-oriented unified management environment [4].

In this chapter, main part of optical communication system structure is clarified. Then, a highlight of several types of PON technologies depending on data multiplexing scheme are reviewed. Next, review 5G MFH/MBH architecture emerged by the 3rd generation partnership project (3GPP) announced with reference to some studies in the field is followed .

3.1 5G requirements

The following set of 5G requirements is gaining industry acceptance.[15]

- ✓ 1-10Gbps connections to end points in the field
- ✓ 1 millisecond end-to-end round trip delay – latency
- ✓ 1000x bandwidth per unit area
- ✓ 10-100x number of connected devices

These demanding specifications are difficult to achieve, and both the transport section of the communication network and the 5G radio require novel technologies. There is a need for solutions that enable independent and flexible customization of latency and reliability characteristics. In fact, if all services were to conform to the most stringent set of standards, the spectral efficiency would be very low [7].

Mobile robots and remote controls are two examples of applications that require minimal latency and great reliability. These new use cases often place extra demands on 5G systems, such as the necessity for high-accuracy positioning for mobile robots or support for isochronous communication. Due to a lack of acceptable wireless technologies that are capable of achieving the stringent standards in industrial automation, the majority of communication technologies employed in the manufacturing industry today are not wireless. Several dedicated Industrial Ethernet technologies, such as Sercos, PROFINET, and Ether CAT, as well as fieldbuses are examples of the current wireline technologies (e.g., PROFIBUS, CC-Link, and CAN). Applications where mobility and untethered connectivity provide value for industrial communications require mobile technologies like 5G, which are essential components. Examples include mobile robots and mobile control panels with safety functions and augmented reality (AR) solutions. The latter can help shop floor employees with their responsibilities by offering additional online information, such as step-by-step instructions or assistance from distant experts [7].

3.2 5G RAN Architectures

In order to support the changing nature of the 5G network, it is clear that one of the most important factors to address is the current and future architecture of the RAN, the link that the radio sites use to connect to the transport network. Not only is this where operators spend most of their money today, but being geographically dispersed, it is also difficult to manage. Therefore, any development or evolution of the RAN to improve the efficiency or reduce the operational costs requires serious consideration [16].

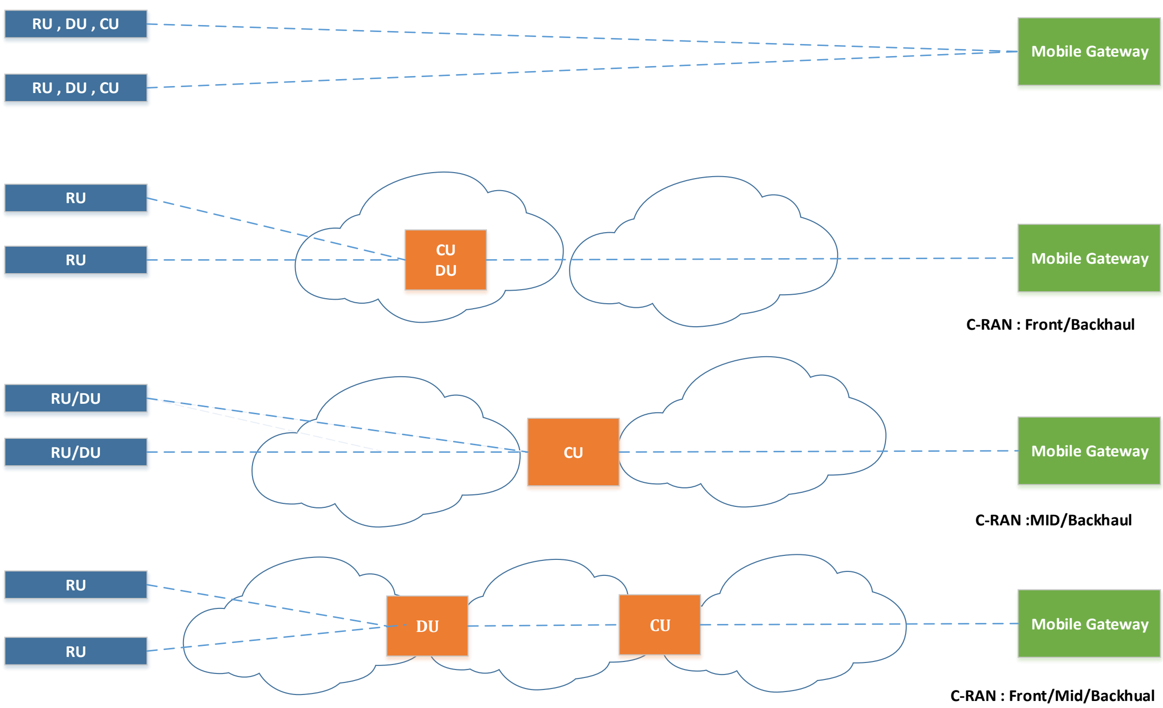


Figure 3-1 : RAN Architecture [16]

Traditionally, we implemented the RAN as a Distributed RAN (D-RAN) architecture, where all the radio functionality (the NodeB or eNodeB) resided in the cell site, which then exchanged IP packets with the mobile core via the backhaul network. The IP protocol was used to carry the traffic streams, and the data rates needed were roughly equivalent to the combined user data rates of user equipment that was utilizing the radios hosted in that cell site. With 4G, and more so with 5G, an alternative to the D-RAN is the disaggregated or Centralized RAN (C-RAN), whereby the upper layers of the radio functions are separated from the lower layers and moved to a shared, centralized location [16].

3.2.1 5G transport

Fifth-generation (5G) mobile access aims to enable a wide range of use cases across a single mobile network and significantly surpass its predecessors in terms of speed, latency, and reliability. In order to achieve this ultimate goal, wireless technology must be revolutionized as well as the architecture and design of mobile networks. The baseband processing unit (BBU) and remote radio head (RRH) can be separated with the deployment of the centralized radio access network (C-RAN) in 4G/Long-Term Evolution (LTE), providing resource pooling at a central point [10].

Typically, the communication between the BBU and the mobile core is referred to as "backhaul," whereas the connectivity between the BBU and the RRH is referred to as "fronthaul". While 4G backhaul is now Ethernet-based, fronthaul employs the Common Public Radio Interface (CPRI), a protocol that carries time-domain digitized I- and Q-radio signals along with additional management and synchronization data in a constant bit rate (CBR) time division multiplex (TDM) format. CPRI-based fronthaul is not practicable for 5G and beyond due to the possibility of fronthaul data rates of tens or even hundreds of gigabits per second, which are one or two orders of magnitude larger than the user data rate [10].

3.3 Optical Fiber communication system

3.3.1 Introduction

The development of semiconductor lasers and the accessibility of low-loss fibers ushered in a new era of optical fiber communication. Over 25 million kilometers of optical fiber have been installed globally, and more than 80% of the world's long-distance traffic is now transported via optical fiber cable [13].

Optical fiber is widely used as a transmission channel for communication systems and supports high-bit-rate over long distance because data is transmitted through glass wires as light waves. Fiber optics communication systems consist of three elements as shown in Figure bellow [4].

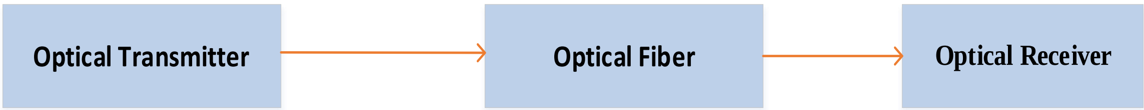


Figure 3-2**:** Optical Communication System [4]

3.3.2 Optical Transmitter

Optical transmitter consists of a light source and its associated drive circuitry to generate optical pulses. It converts the information carrying electrical signals to optical signals and launches the optical signals into an optical fiber. The most common light sources are Light Emitting Diodes (LEDs) and Laser Diodes (LDs) [12][4].

LEDs emit light through spontaneous emission and are used extensively in fiber optic communication systems due to their small size, long lifetime and low cost. They are used in short distance and low bandwidth networks. LEDs emit light through amplification of radiation by simulated emission. Laser has a higher output power than LED and so they are capable of transmitting information over longer distances and provide high bandwidth communication [12].

3.3.3 Optical Fiber

An optical fiber consists of a central core clad with a material of slightly lower refractive index, as shown in the figure bellow. A fiber is referred to as a step-index fiber if the refractive index of the core is constant. Most of the fibers are made from glass. Doping the silica with GeO2 increases the core's refractive index. The cladding is pure silica. To safeguard the fiber from moisture and abrasion, a polymer jacket is used. For short-distance and low-bit-rate transmission systems, plastic fibers can be used. They are: (i) inexpensive, (ii) flexible, and (iii) easy to install and connect. However, due to their high absorption, they do not transmit light well. In general, glass fibers are employed for long-distance and high-bit-rate systems[13].

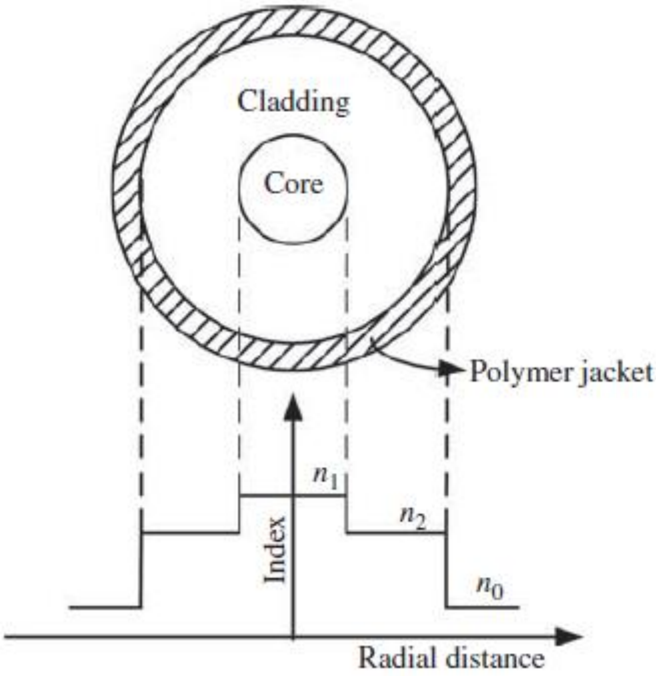


Figure 3-3: Optical Fiber [13]

3.3.4 Optical Receiver

A photodetector, an amplifier, and signal processing circuitry make up an optical receiver. The receiver's main task is to turn the optical energy leaving a fiber's end into an electric signal, then boosting this signal to a sufficient level to pass through the receiver amplifier and be processed by the electronics that come next [12].

The first element of a receiver is a photodetector. The photodetector detects the luminous power falling on it and transforms the variation of this optical power into an electrical current that varies in accordance with that variation. The photodetector must adhere to very strict performance specifications because the optical signal is typically weaker and distorted when it leaves the fiber's end. Among the most important of these criteria are a high response or sensitivity in the emission wavelength range of the optical source being utilized, a minimal amount of noise addition to the system, and a quick response speed or enough bandwidth to accommodate the necessary data rate. The photodetector should also be resistant to temperature changes, consistent with the optical fiber's physical specifications, reasonably priced in comparison to the other system components, and have a long operational life [16].

These procedures inadvertently produce a variety of noises and distortions, which could result in inaccuracies in the interpretation of the received signal. The current produced by the photodetector may be quite weak depending on the strength of the optical signal received, and it is badly impacted by the random noises related to the photo detecting process. When this photodiode's electric output is amplified, the signal becomes even more distorted by extra noises produced by the amplifier's circuits. Since the noise sources operating in the receiver typically determine the lowest limit for the signals that may be processed, noise considerations are crucial when designing optical receivers. It is far more difficult to develop an optical receiver than it is to design an optical transmitter because the receiver must be able to identify weak, distorted signals and decide what kind of data was sent based on an amplified and reshaped version of the distorted signal [12].

3.3.5 Optical Amplifiers

An optical signal passing through a fiber experiences loss of optical power. The loss is significant as the transmission distance increases and cannot be ignored. When the signal propagating a long-distance optical fiber becomes extremely weak, it is necessary to amplify the light using an optical amplifier. An optical amplifier amplifies light as it is without converting the optical signal to an electrical signal, and is an extremely important device that supports the long-distance optical communication networks of today [12].

Before the use of optical amplifiers, In order to account for fiber loss, electrical amplifiers were used in fiber-optic communication systems. The optical signal was first converted to the electrical signal (O/E conversion) using a photodetector and then converted back to the optical domain (E/O conversion) after amplification in the electrical domain. However, for multi-channel optical communication systems, this kind of optoelectronic regenerator is pricey. With the development of optical amplifiers, it is no longer necessary to perform O/E and E/O conversion before amplifying an optical signal. The optical signal can be amplified physically using a variety of methods[13].

Population inversion is accomplished in semiconductor optical amplifiers (SOAs) using an electrical pump (power supply. Electrons are stimulated to recombine with holes and produce photons as a result of stimulated emission in the presence of signal photons with energy close to the band gap.. Thus, the input signal photons are amplified. In EDFAs, an optical pump is used to achieve population inversion. The excited erbium ions release light via stimulated emission and transition to the ground state when signal photons are present. In Raman amplifiers, a signal photon of lower energy is created by an optical pump giving up some of its energy, and the remaining energy manifests as molecular vibration (or optical photons). This is known as stimulated Raman scattering (SRS). In the event that there is already a signal photon of lesser energy, SRS amplifies it [13].

3.3.6 Optical Filters

Optical filters require a wavelength-selective mechanism. Through the use of the dense wavelength division multiplexing (DWDM) technology, it is now possible to expand the data transmission capacity thanks to the development of narrowband optical filters [25][26].

3.3.6.1 Gaussian Optical Filter

a Gaussian filter is a filter whose impulse response is a Gaussian function. It has the properties of having no overshoot to a step function input while minimizing the rise and fall time. A Gaussian filter have the best combination of suppression of high frequencies while also minimizing spatial spread, being the critical point of the uncertainty principle. These properties are important in areas digital telecommunication systems [27].

3.3.7 Optical Multiplexer

At the transmitting endo of a transmission system a wavelength multiplexer is required to combine the optical signals of each transmitter. The outputs of several transmitters, each operating at its own carrier wavelength, are combined inside a multiplexer. A fiber link is used to transmit the multiplexed signal [25].

3.3.8 Optical Demultiplexer

At the Receiving of a transmission system, a wavelength demultiplexer is required to separate the optical signals into appropriate detection channels at different wavelengths for signal processing.[12]. Each channel is delivered to its own receiver using a demultiplexer [25]. The WDM signal consisting of multiple wavelength components is incident on the grating. Different wavelength components diffract at various angles, and output fibers collect them [18].

3.3.9 Optical couplers

An optical coupler's function is to combine optical signals coming into its many input ports and divide them equally among its output ports. Couplers, as opposed to demultiplexers, do not attempt to split distinct channels, hence they do not include wavelength-selective elements. The numbers of input and output ports need not be the same. Several kinds of couplers have been developed for LAN applications [25].

For all wavelengths, the splitting is typically performed equally, giving each of the N outputs 1/N of the power entering the device. A common fabrication method for an N ×N splitter is to fuse together N single-mode fibers that have thinned core-cladding regions over a length of few millimeters. In general, an N to M coupler has N inputs and M outputs [12].

3.4 WDM Concepts

Another way to increase fiber transmission capacity is by using wavelength division multiplexing (WDM). The fundamental idea behind WDM is to broadcast multiple independent information streams simultaneously over a single cable using various sources operating at slightly different wavelengths. Figure-3.4 shows the basic WDM concept. Here N independent optically formatted information streams, each transmitted at a different wavelength, are combined by means of an optical multiplexer and sent over the same fiber. Keep in mind that the data rates for each of these streams may differ. Each information stream maintains its individual data rate after being multiplexed with the other traffic C streams, and still operates at its unique wavelength. The WDM approach is conceptually equivalent to frequency division multiplexing (FDM), which is utilized in microwave radio and satellite systems [12].

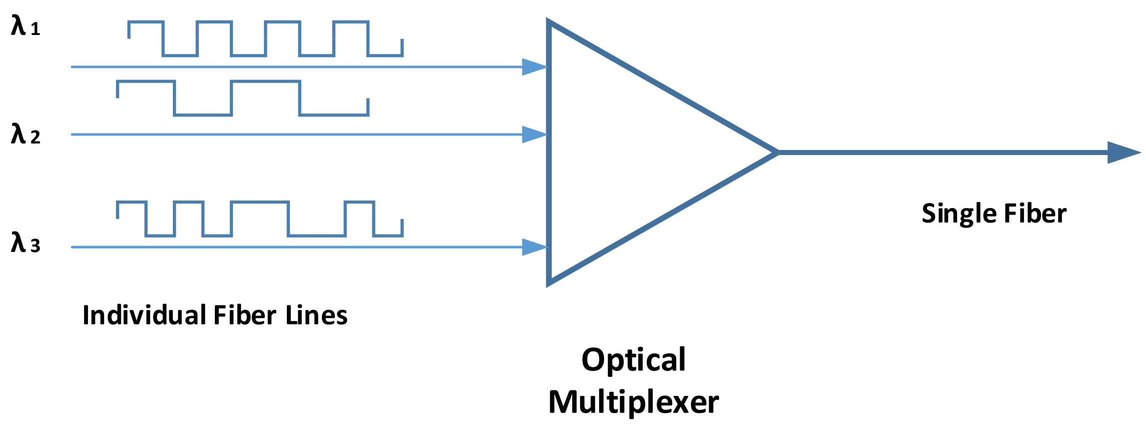


Figure 3-4 : Basic concept of wavelength division Multiplexing [12]

Despite the fact that WDM techniques were first studied in the 1970s, it eventually became clear that utilizing high-speed electronic and optical devices to transmit only a single wavelength on a fiber was generally simpler than employing WDM, which requires a more complicated system. But in the early 1990s, WDM's acceptance dramatically increased for a variety of reasons. These improvements include the creation of new fiber types that offer improved performance for multiple-wavelength operation at 1550 nm, the development of WDM devices that can separate closely spaced wavelengths, and the creation of optical amplifiers that can completely increase C-band optical signal levels in the optical domain [12].

3.4.1 Passive Optical Networks

Ever since optical fibers were available, researchers began to look for ways to apply them to the access network, and particularly fiber to the home (FTTH). The simplest way to apply fiber to the access is to simply replace the copper wires with fiber strands, resulting in a point-to-point fiber network .However, this network tends to be the maximum of cost: it uses the most fiber, and each home requires two transceivers (one at the home and one at the local exchange).In the 1980s, a new form of optical access topology was invented, based on passive optical networking (PON).The key idea was that the shared feeder fiber would be connected to the distribution fiber using a purely optical component (e.g. a splitter or wavelength multiplexer). This achieves the fiber savings without requiring electrical power at the remote terminal [18].

The simplest form of PON is that based on optical splitters. At an optical level, the splitter provides directional optical coupling between one or more common fibers and multiple distribution fibers. Signals traveling downstream are split to all the users. Signals traveling upstream are combined. Optical reflections cause some cross coupling of the two directions.
These reflections can jam the transmission, and therefore require a means of duplexing the two directions on a single fiber. There are two methods used to eliminate this problem. The first is using time division duplexing (TDD), wherein first the OLT transmits, then the channel is allowed to clear (due to the round-trip time of flight of the signals), and then the ONUs are allowed to transmit. The second method is wavelength division duplexing (WDD) that uses a different color of light for each direction [18].

3.4.1.1 TDM PON

The simplest media access control (MAC) protocol is time division multiplex. In the downstream, each ONU receives a copy of the OLT's output. The transmission protocol on the PON provides some form of tag on each data frame to enable the ONU to select its own data and discard the rest. However, in the upstream, all the ONU's transmissions are combined passively, so if two ONUs transmit at the same time, their transmissions is jammed. The OLT must coordinate the transmissions of the ONUs so that they arrive at the splitter at different times.

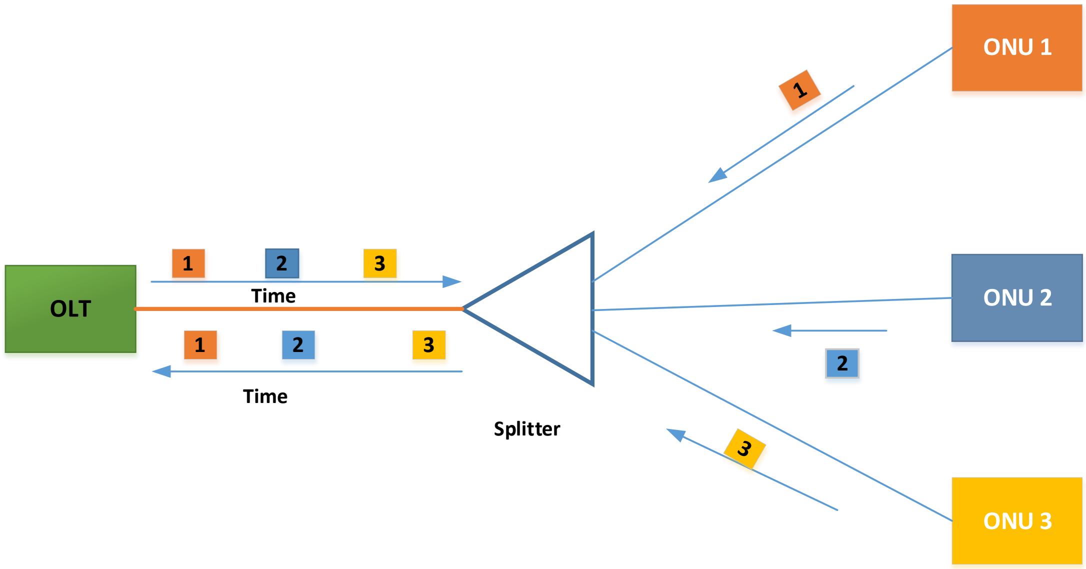


Figure 3-5: TDM-PON Operation [18]

Any TDM-PON system has the issue of bandwidth allocation. Static allocation of bandwidth to each ONU is simple, but it does not allow the system to respond to the users' varying demand levels. It is far more efficient to give each ONU a bandwidth that is somewhat proportional to its traffic demand. The process of doing this is termed dynamic bandwidth allocation (DBA) and is a feature of all modern PONs [18].

3.4.1.2 WDM PON

WDM-PON as that which uses WDM as the primary method of multiplexing multiple ONUs onto a shared ODN. This implies either one or two wavelengths per endpoint, and this is the key differentiator from other PONs that use WDM as a sub feature (such as TDM-PON, which uses WDM for duplexing, or hybrid PONs, which has a pair of wavelengths per sub-PON) [18].

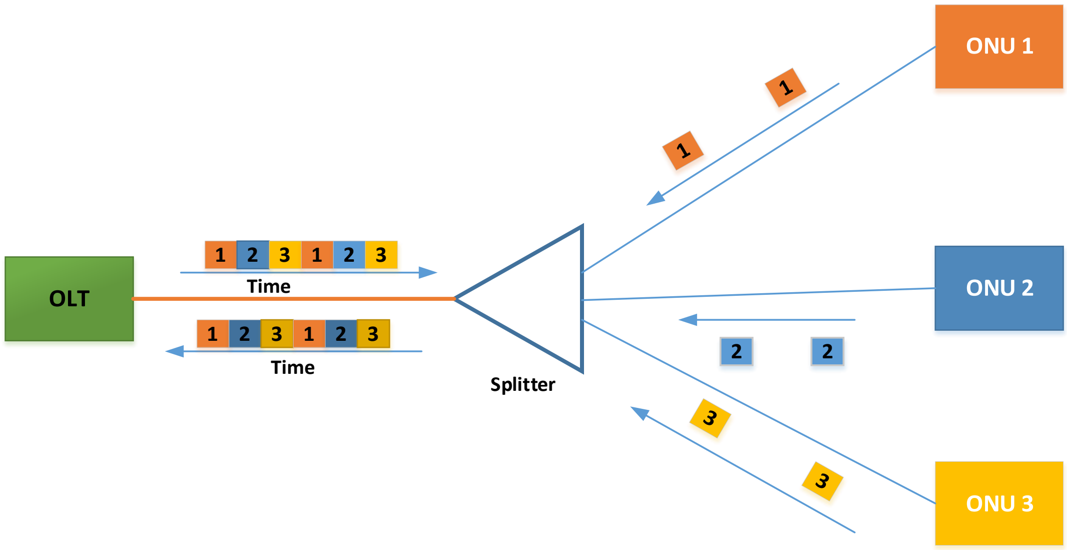


Figure 3-6 WDM-PON Operation [18]

3.5 BIT ERROR RATE Measurements

The Bit Error Rate (BER) is an important performance quality indicator of a digital communication link [12]. It is the rate at which errors are being committed by a receiver in correctly recognizing 1's and 0's. Thus, if in receiving n pulses (bits) consisting of a random sequence of 1's and 0's the receiver commits an average of r errors, the bit error rate is defined as the ratio of r to n. As an example, let us assume that in receiving 10 billion pulses the receiver commits five errors on average; the BER is $5 * 10^{-10}$. If this is the BER for a 2.5-Gb/s communication system, then since in 1 second there would be $2.5 * 10^{9}$ bits, the average number of errors committed per second would be 1.25. If the system operates at 10 Gb/s with the same BER, the number of errors per second would be 5. A typical BER requirement of current communication systems is 10^{-12} to 10^{-15} [19,28].

3.6 Optical Signal to Noise Ratio Measurements

For single-wavelength links without optical amplifiers, measuring SNR and its corresponding BER is simple. However, in multi-span optically amplified DWDM networks, the OSNR, rather than the optical signal power that reaches the receiver, limits system performance. Although one could demultiplex the incoming DWDM traffic and then do BER estimates on each individual wavelength channel, an optical spectrum measurement can be performed with an optical spectrum analyzer (OSA) to derive the OSNR for each individual channel [12,19].

Since the OSNR generated from the optical spectrum is an average-power, low-speed measurement, it cannot reveal how temporal limitations affect channel performance. The OSNR, however, offers indirect BER information for a preliminary performance analysis of a multichannel system or for providing forewarning of a potential BER degradation on a specific WDM channel because it can be connected to the BER. $OSNR(dB) = 10\log(\frac{P_{ave}}{P_{ASE}})$ [12,25].

Chapter Four

4 System Model

In this section Coherent Heterodyne model transmission systems is discussed and at the end of the section, back-to-back model .

4.1 Coherent Heterodyne Model

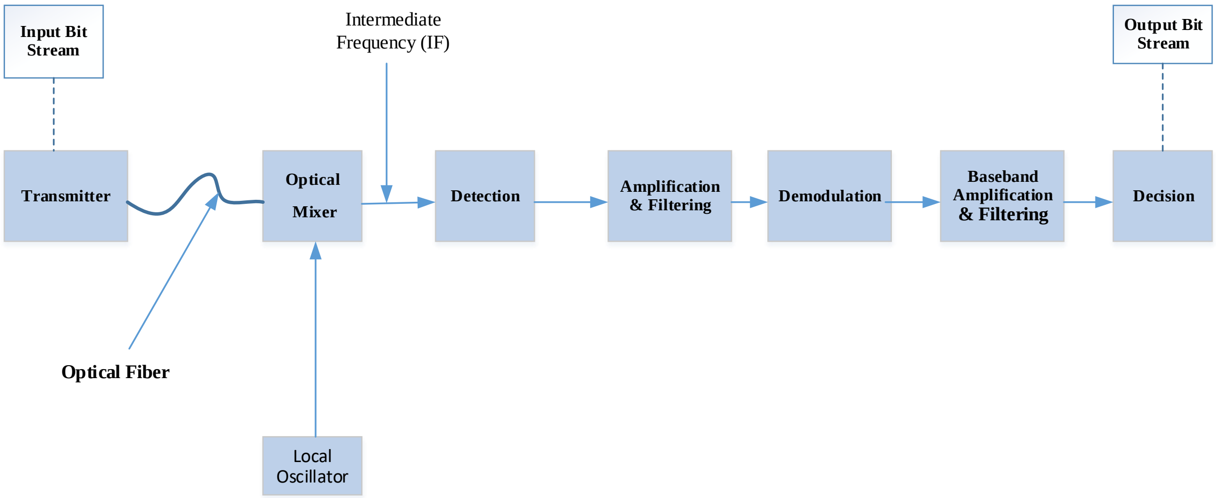


Figure 4-1 Coherent Heterodyne System

The main idea in the coherent detection technique is to amplify the incoming optical signal by coupling it to a locally generated continuous wave optical field. The coupling of incoming optical signal with locally generated continuous wave produces other signal with different frequencies, which are filtered by filters [12].

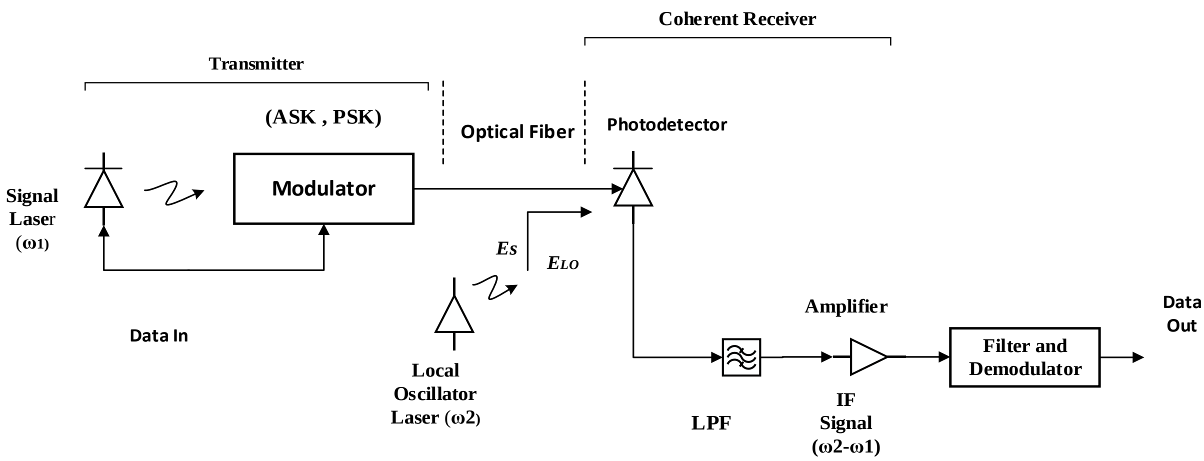


Figure 4-2 coherent light-wave system [12]

Figure above shows a coherent light-wave system. On transmitter side, the incoming data streams are modulated and transmitted using the optical fiber. On the receiver side, the signal from the optical fiber is coupled with locally generated signal .

For mathematical analysis of the system, let us consider the electric field of transmitted signal having the form

$$S(t) = A_s \cos(2\pi f_s t + \theta_s) \text{ ---------------------------------------(4.1)}$$

Where, A_s is the amplitude of the optical signal field, f_s is the optical signal carrier frequency, and θ_s is the phase of the optical signal. The Amplitude, frequency or phase of the optical signal can be modulated

4.1.1 Modulations Techniques

4.1.1.1 Amplitude Modulation

In the Equation $S(t) = A_s \cos(2\pi f_s t + \theta_s)$ when the amplitude A_s is varied in accordance with a message signal $m(t)$ while keeping f_s and θ_s constant, the resulting scheme is known as amplitude modulation. Suppose the amplitude is proportional to the message signal $m(t)$

$$A(t) = K_a m(t) \text{ --(4.2)}$$

where k_a is amplitude sensitivity. Now, the carrier is said to be amplitude modulated. The modulated signal can be written as

$$S(t) = k_a m(t) \cos(2\pi f_s t + \theta_s) \text{ ---------------------------------------(4.3)}$$

When the message signal m(t) is a digital signal, the modulation scheme is known as amplitude-shift keying (ASK) or on–off keying (OOK). In general, to transmit bit ‘1’, a sinusoid of certain amplitude A1 is sent and to transmit bit ‘0’, a sinusoid of amplitude A2 is sent.

4.1.1.2 Phase Modulation

When the phase θ_s of the carrier is varied in accordance with the message signal m(t) while keeping the amplitude $A(t)$ and frequency f_s constant, the resulting scheme is known as phase modulation. Suppose the phase is proportional to the message signal,

$$\theta(t) = k_p m(t) \quad \text{--(4.4)}$$

where k_p is called the phase sensitivity. Now, the optical carrier is said to be phase modulated. The modulated signal can be written as

$$S(t) = A\cos[2\pi f_s t + k_p m(t)] \quad \text{---------------------------------------(4.5)}$$

For digital signal

$$m(t) = \begin{cases} -V, & for\ bit\ "1" \\ V, & for\ bit\ "0" \end{cases}$$

Where $V = \frac{\pi}{2} k_p$

$$s(t) = \begin{cases} A*\sin(2\pi f_s), & for\ bit\ '1' \\ -A*\sin(2\pi f_s), & for\ bit\ '0' \end{cases} \quad \text{----------------------(4.6)}$$

When the message m(t) is a digital signal, the modulation scheme is known as phase-shift keying (PSK) or binary phase-shift keying (BPSK). In general, PSK can be described as a scheme in which a bit ‘1’ is transmitted by sending a sinusoid of phase $\theta 1$ and a bit ‘0’ is transmitted by sending a sinusoid of phase $\theta 2$.

4.1.1.3 Frequency Modulation

When the frequency f_s of the carrier is varied in accordance with the message signal $\mathrm{m(t)}$ while keeping the amplitude $A(t)$ and frequency θ_s constant, the resulting scheme is known as frequency modulation. Suppose the phase is proportional to the message signal,

$$m(t) = \begin{cases} m_1, & for\ bit\ '1' \\ m_2, & for\ bit\ '0' \end{cases}$$

The transmitted signal within a bit interval [0, Tb] can be written

$$s(t) = A_s \cos[\varphi(t)] \quad \text{--(4.7)}$$

Where

$$\varphi(t) = \begin{cases} 2\pi f_1 t, & for\ bit\ '1' \\ 2\pi f_2 t, & for\ bit\ '0' \end{cases}$$

4.1.2 Demodulation Techniques

At receiver side in coherent systems, a locally generated optical wave is added to the Incoming signal and then coupled signal is detected.

If LO has the form,

$$E_{LO} = A_{LO}\cos[\omega_{LO} + \phi_{LO}t] \text{---------------------------------------(4.8)}$$

where, A_{LO} is the amplitude of the LO signal field, $\omega_{LO}t$ is the optical LO carrier frequency, and $\phi_{LO}t$ is the phase of the optical LO. Then the detected current $I_{coh}(t)$ is proportional to the square of the total electric field of the signal falling on the photodetector. Here, we have to mention that LO wave is coupled with received signal before (on the surface) the photodetector

$$I_{coh}(t) = (E_s + E_{LO})^2 \text{---------------------------------------(4.9)}$$

$$= \frac{1}{2}A_s^2 + \frac{1}{2}A_{LO}^2 + A_s A_{LO}\cos[(\omega_s - \omega_{LO})t + \varphi_s(t) - \varphi_{LO}(t)]\cos\theta(t) \text{---------------------------(4.10)}$$

Where

$$\cos\theta(t) = \,|\frac{E_s E_{LO}}{|E_s||E_{LO}|}$$

Represents the polarization misalignment between the signal wave and LO wave.

Since the optical power is proportional to the intensity at the photo detector, then we have

$$P(t) = P_s + P_{LO} + 2\sqrt{P_S P_{LO}}\cos[(\omega_s - \omega_{LO})t + \varphi_s(t) - \varphi_{LO}(t)]\cos\theta(t) \text{---------------------------(4.11)}$$

where, P_s and P_{Lo} are the signal and LO optical powers, respectively, with $P_{LO} >> P_s$. Thus, we see the angular frequency difference $\omega_{IF} = \omega_s - \omega_{LO}$ is an intermediate frequency, and the phase angle $\varphi(t)=\varphi_s(t)-\varphi_{LO}(t)$ is the time-varying phase difference between the signal and LO levels. Normally, ω_{IF} is in radio frequency range of tens or hundreds of megahertz

4.1.3 Detection

Light energy is always transmitted or absorbed in discrete units known as quanta or photons. In all experiments used to show the existence of photons, the photon energy is found to depend only on the frequency v. This frequency, in turn, must be measured by observing a wave property of light. A photon's energy E and frequency v are related by the following equation: $E=h\upsilon$, Where $h=6.625*10^{-34}J$ is Planck's constant. [12]
When light is incident on an atom, a photon can transfer its energy to an electron within this atom, thereby exciting it to a higher energy level. The electron receives either all or none of the photon energy during this operation. The energy that the electron absorbs must perfectly match the energy needed to excite the electron to a higher energy level. Conversely, an electron in an excited state can drop to a lower state separated from it by an energy $h\nu$ by emitting a photon of exactly this energy.[12]
In direct detection, the photodetector (light pulse receiver) reacts to changes in the power level (intensity of light) that strikes it directly. The photodetector converts the fluctuations in optical power level to the original electrical signal format. The optical carrier's frequency and phase are not taken into consideration [12]. This limits the data transmission rate.

On the other hand, coherent detection takes the typical ones and zeroes in a digital signal (the blinking on and off of the light in the fiber) and uses sophisticated technology to modulate the amplitude and phase of that light and send the signal across each of two polarizations. This, in turn, imparts considerably more information onto the light speeding through a fiber optic cable [12]. Coherent detection appears to be a more appealing design strategy than direct detection as the demands for more bandwidth for 5G transport architecture grow since it allows for a higher spectral efficiency.[4]

In the equation 4.11, if the received signal and the Local Oscillator (LO) wave have the same frequency, then ω_{IF}= 0 and the detection is homodyne detection. When the received signal and the Local Oscillator (LO) wave have different frequencies, $\omega_{IF}\neq 0$, the heterodyne detection is the case.

4.1.3.1 Heterodyne detection

When compared to homodyne receivers, heterodyne receivers are substantially simpler to implement. Heterodyne detection can be used in the following types of modulation types: On of shift keying, Frequency shift keying, or phase shift keying.

In the equation

$$P(t) = P_s + P_{LO} + 2\sqrt{P_S P_{LO}}\cos[(\omega_s - \omega_{LO})t + \varphi_s(t) - \varphi_{LO}(t)]\cos\theta(t) \text{ ----------------------------(4.12)}$$

Since $P_{LO} >> P_s$, we can ignore P_s. The receiver output current then contains a dc term given by

$$i_{dc} = \frac{\eta q}{h\upsilon} P_{LO} \text{ --(4.13)}$$

where, η, is the quantum efficiency, q is the electron charge = 1.60218 ×10-19 C, h is Planck's constant with value $6.625*10^{-34} J$ and υ is the frequency. In other hand, time varying IF term given by

$$i_{IF} = \frac{2\eta q}{h\upsilon}\sqrt{P_S P_{LO}}\cos[\omega_{IF} t + \varphi(t)]\cos\theta(t) \text{ -------------------------------------(4.14)}$$

Normally, the dc current (i_{dc}) is filtered in the receiver and IF current (i_{IF}) is amplified. Information then can be recovered from the IF current using conventional RF demodulation techniques.

4.1.3.2 Heterodyne Synchronous detection

By selecting an intermediate frequency (IF) that is in the microwave range (~1 GHz), the local oscillator's frequency is different from the incident signal's carrier frequency. The current generated at the photodiode oscillates at the intermediate frequency and is passed through a bandpass filter (BPF) centered at this frequency ω_{IF} .

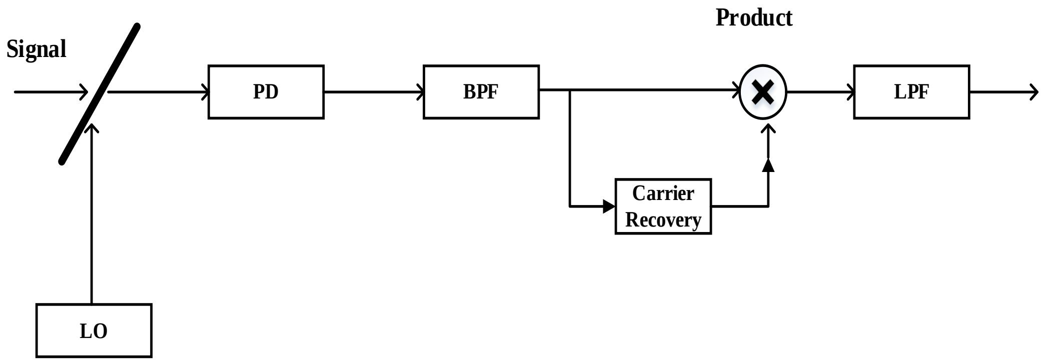


Figure 4-3 : Heterodyne Synchronous detection

When using synchronous demodulation, the microwave carrier $\cos(\omega_{IF}t)$ is recovered using a clock circuit as shown in the figure above. Then, $If(t)$ is filtered by a low-pass filter after being multiplied by this clock signal.

4.1.3.3 Heterodyne Asynchronous detection

After the current generated at the photodiode is passed through a bandpass filter (BPF), an envelope detector is used to recover the microwave carrier cos (ω_{IF} t) as shown in the figure bellow. Then, the output of the envelop detector is filtered by a low-pass filter.

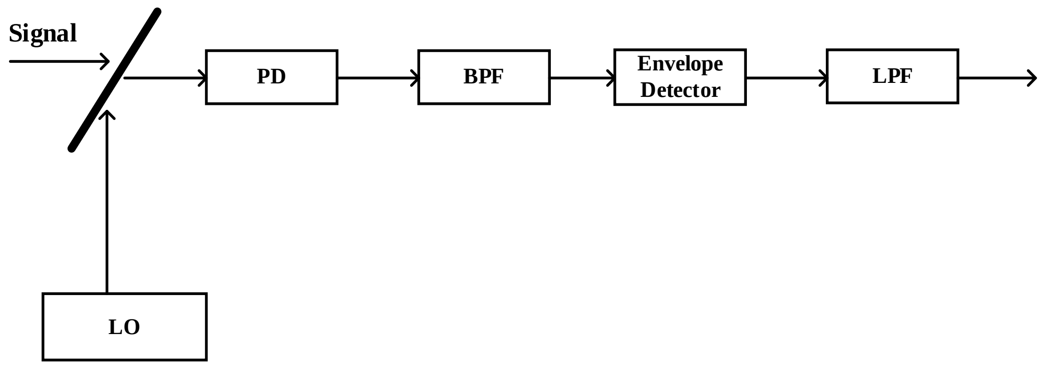


Figure 4-4 Heterodyne Synchronous detection

4.1.4 BER Comparisons

Now we make a comparison of the several coherent detection methods. Typically, bit-error rate is used to describe how well a digital communication system performs. The BER depends on the signal-to-noise ratio (SNR) and the probability density function (PDF) at the receiver output (at the input to the comparator). Since the PDF for high local oscillator powers is Gaussian for both homodyne and heterodyne approaches, the BER simply depends on the signal-to-noise ratio. Since SNR at the receiver output is directly proportional to the received optical signal power, one can quantify receiver sensitivity in terms of this SNR. Since conventionally coherent detection systems' receiver sensitivity has been characterized in terms of the average number of photons required to achieve a 10^{-9} BER, we shall use that criterion here [12].

4.1.5 Heterodyne Detection Schemes

In comparison to the homodyne situation, the analysis for heterodyne receivers is more challenging because the photodetector output appears at an intermediate frequency ω_{IF}. One appealing trait of heterodyne receivers is that they can employ either synchronous or Asynchronous detection [12].

4.1.5.1 BER Analysis for PSK Heterodyne system

A carrier-recovery circuit, often a microwave phase-locked loop (PLL), is used in synchronous PSK detection to create a local phase reference. The intermediate-frequency carrier is recovered by mixing the output of the PLL with the intermediate-frequency signal. A low-pass filter is then used to retrieve the baseband signal. The BER for synchronous heterodyne PSK is given by [12].

$$BER = \frac{1}{2} erfc\sqrt{\eta \overline{N_P}} \quad \text{---(4.15)}$$

Asynchronous detection is a less complicated yet reliable method that does not make use of a PLL. This technique is called differential PSK or DPSK. Here a simple one-bit delay line replaces the carrier-recovery circuit. Given that the PSK method uses changes in optical phase to encode information, the mixer gives a positive or negative output depending on whether the received signal's phase has changed since the previous bit.[12]

Thus, from this output, the sent information is reconstructed. This DPSK technique has a sensitivity close to that of synchronous heterodyne detection of PSK, with a bit-error rate of [12]

$$BER = \frac{1}{2} \exp(-\eta \overline{N_p}) \quad \text{---(4.16)}$$

4.1.5.2 BER Analysis for OOK Heterodyne system

For synchronous heterodyne OOK detection the BER is given by [12]

$$BER = \frac{1}{2} erfc\sqrt{\frac{1}{2}\eta \overline{N_P}} \quad \text{---(4.17)}$$

For asynchronous heterodyne OOK detection the BER is given by [12]

$$BER = \frac{1}{2}\exp(-\frac{1}{2}\eta \overline{N_p}) \text{ --(4.18)}$$

4.1.5.3 Frequency Shift Keying (FSK)

For synchronous heterodyne OOK detection the BER is given by [12]

$$BER = \frac{1}{2} erfc\sqrt{\frac{1}{2}\eta \overline{N_P}} \text{ --(4.19)}$$

For asynchronous heterodyne OOK detection the BER is given by [12]

$$BER = \frac{1}{2}\exp(-\frac{1}{2}\eta \overline{N_p}) \text{ --(4.20)}$$

4.1.6 Number Of Photons for Unity Quantum Efficiency

4.1.6.1 For PSK Heterodyne system

For synchronous heterodyne PSK, the BER as show in equation 4.15 is

$$BER = \frac{1}{2} erfc\sqrt{\eta \overline{N_P}}$$

To achieve 10^{-9} BER and Quantum efficiency (η)of 1

$$10^{-9} = \frac{1}{2} erfc\sqrt{1 * \overline{N_P}}$$

$$\overline{N_P} = erfc^{-1}(2*10^{-9})$$

$$\overline{N_P} = 18$$

For asynchronous heterodyne PSK, the BER formula is shown in equation 4.16

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

To achieve 10^{-9} BER and Quantum efficiency (η) of 1

$$10^{-9} = \frac{1}{2}\exp(-1\overline{N_P})$$
$$2*10^{-9} = \exp(-1*\overline{N_P})$$
$$2*10^{-9} = \exp(-\overline{N_P})$$
$$2*10^{-9} = 10^{-\overline{N_P}}$$
$$\overline{N_P} = 20$$

4.1.6.2 For OOK Heterodyne system

For synchronous heterodyne OOK, the BER for as shown in equation 4.17 is

$$BER = \frac{1}{2}erfc\sqrt{\frac{1}{2}\eta\overline{N_P}}$$

To achieve 10^{-9} BER and Quantum efficiency (η) of 1

$$BER = \frac{1}{2}erfc\sqrt{\frac{1}{2}\eta\overline{N_P}}$$
$$10^{-9} = \frac{1}{2}erfc\sqrt{\frac{1}{2}\overline{N_P}}$$
$$\overline{N_P} = 2*erfc^{-1}(2*10^{-9})$$
$$\overline{N_P} = 36$$

For asynchronous heterodyne OOK, the BER formula as shown in equation 4.18 is

$$BER = \frac{1}{2}\exp(-\frac{1}{2}\eta\overline{N_P})$$

To achieve 10^{-9} BER and Quantum efficiency (η) of 1

$$10^{-9} = \frac{1}{2}\exp(-\frac{1}{2}*1*\overline{N_P})$$
$$2*10^{-9} = \exp(-\frac{1}{2}\overline{N_P})$$
$$2*10^{-9} = 10^{-\frac{1}{2}\overline{N_P}}$$
$$\overline{N_P} = 40$$

4.1.6.3 FSK Heterodyne system

For synchronous heterodyne OOK , the BER formula shown in equation 4.19 is

$$BER = \frac{1}{2} erfc\sqrt{\frac{1}{2}\eta \overline{N_P}}$$

To achieve 10^{-9} BER and Quantum efficiency (η) of 1

$$10^{-9} = \frac{1}{2} erfc\sqrt{\frac{1}{2} * 1 * \overline{N_P}}$$

$$2*10^{-9} = erfc\sqrt{\frac{1}{2} * \overline{N_P}}$$

$$\overline{N_P} = 2 * erfc^{-1}(2*10^{-9})$$

$$\overline{N_P} = 36$$

For asynchronous heterodyne FSK, the BER formula as shown in equation 4.20 is

$$BER = \frac{1}{2}\exp(-\frac{1}{2}\eta \overline{N_P})$$

To achieve 10^{-9} BER and Quantum efficiency (η) of 1

$$10^{-9} = \frac{1}{2}\exp(-\frac{1}{2} * 1 * \overline{N_P})$$

$$2*10^{-9} = \exp(-\frac{1}{2} * \overline{N_P})$$

$$2*10^{-9} = \exp(-\frac{1}{2} * \overline{N_P})$$

$$2*10^{-9} = 10^{-\frac{1}{2}\overline{N_P}}$$

$$\overline{N_P} = 40$$

4.1.7 Comparison of Modulation Techniques

The Number of Photons for Unity Quantum Efficiency of different modulation techniques with heterodyne receiver found in section 4.6 using BER formulas in equations 4.15 to 4.20 can be summarized and compared as follows.

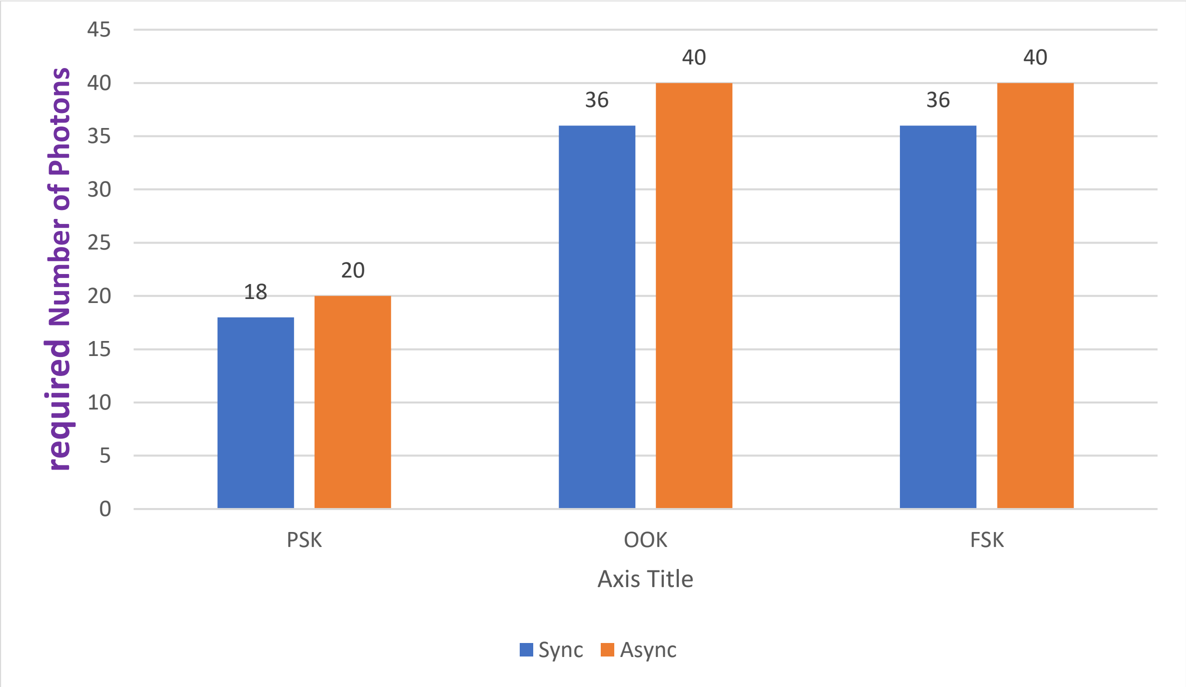


Figure 4-5 comparison of various modulation techniques for heterodyne detection

From the result summarized in the chart above, heterodyne detection, using PSK is the most attractive technique due to its highest sensitivity.

4.2 Back-to-back model

Using the back-to-back coherent heterodyne model, the transmitter is directly connected to the receiver without fiber. Since there is no fiber, there are no dispersion effects like polarization mode dispersion, chromatic dispersion and others.

4.3 Selected Modulation Technique

From the comparison of different modulation techniques for heterodyne detection in section 4.1.7 above, using PSK is the most attractive technique due to its highest sensitivity. Hence, this technique is chosen for the proposed system and used in the simulation in the next section.

Chapter Five

5 Simulation, Result and Discussion

In this chapter, WDM Dual Polarization 8-PSK PON i.e. (WDM 8-QPSK PON) topology is presented. A block diagram of the topology is presented as an introduction followed by simulation of 8*8 wavelengths.

As mentioned in the introduction and background sections, high bandwidth (in order of GB) and low latency (sub millisecond) are the major requirements of 5G transport.

For the proposed system, we have chosen WDM PON over TDM based PON since it doesn't need DBA which in turn result in low latency and higher data rate capacity due to the fact that different wavelengths are used for different services.

Among modulation techniques, coherent heterodyne PSK modulation is chosen because it has higher sensitivity compared to FSK and ASK [i.e., requires fewer number of photons for Unity Quantum efficiency]. There are different phase number options for PSK like BPSK, QPSK,8-PSK, but 8-PSK is usually the highest order PSK constellation deployed since with more than 8 phases , the error-rate becomes too high. Hence 8-PSK is selected for this scheme. It multiplies the capacity since 3 bits are transmitted within one symbol.

To Further increase the transmission capacity, we have used polarization multiplexing i.e., horizontal and vertical polarizations are used to carry different signal on the same wave length. Using Two polarizations doubles the 8-PSK system capacity [6 bits are transmitted within one symbol].

Regarding the number of optical channels, we chose 8 channels for uplink and 8 channels for downlink considering the system complexity and its effect on computation using the above schemes, a bit rate of $2 * R_s * \log_2 M$ per channel per second can be achieved, where N_{ch} is the number of Channels, Rs is Symbol Rate, M is the Modulation Technique. For symbol rate of 50 G Symbol per second, and 8 for phase variation [since we use 8-PSK], we get 300 GBps per channel and a total of 2.4 TB/s .

5.1 Topology

To achieve a 300 GBps per channel and a total of 2.4 TB/s data rate, we used the scheme shown in the Figure 5-1. Since network elements between the Optical Line Terminator and Optical Node Unit should be passive and the power usage at Optical Node units should be minimized, the optical signal should be boosted before transmission and the received signal should be amplified. The scheme is designed to support a distance of 100 KM. For boosting optical signal power before transmission, a booster is used and to amplify the received signal an amplifier is used, both with OLT.

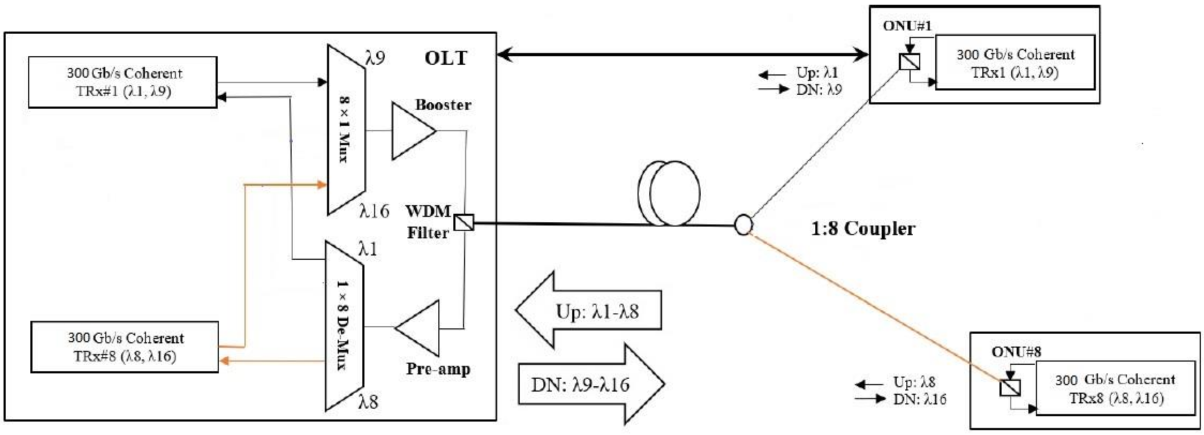


Figure 5-1 General Architecture WDM PON system

5.2 Wavelength

For the simulation, we used wavelengths in the C-band since we get minimum loss through the fiber in this band. Eight wavelengths for downlink and Eight wavelengths for uplink are chosen starting from 1,537.79 nm with an increment of 0.4 nm up to 1,540.56 nm. The corresponding frequencies are 194.94 THz to 194.60 THZ spaced 50 GHz apart. The wavelengths from 1,558.17 nm to 1,560.97 nm are used for downlink while wavelengths 1,537.79 nm to 1,540.56 nm are used for uplink.

No.	Wavelength	Frequency	Used for
λ1	1,537.79 nm	194.95 THz	Uplink
λ2	1,538.19 nm	194.90 THz	Uplink
λ3	1,538.58 nm	194.85 THz	Uplink
λ4	1,538.98 nm	194.80 THz	Uplink
λ5	1,539.37 nm	194.75 THz	Uplink
λ6	1,539.77 nm	194.70 THz	Uplink
λ7	1,540.17 nm	194.65 THz	Uplink
λ8	1,540.56 nm	194.60 THz	Uplink
λ9	1,558.17 nm	197.53 THz	Downlink

λ10	1,558.57 nm	197.48 THz	Downlink
λ11	1,558.97 nm	197.43 THz	Downlink
λ12	1,559.37 nm	197.38 THz	Downlink
λ13	1,559.77 nm	197.33 THz	Downlink
λ14	1,560.17 nm	197.28 THz	Downlink
λ15	1,560.57 nm	197.23 THz	Downlink
λ16	1,560.97 nm	197.18 THz	Downlink

Table 5-1 Wavelengths used in the simulation

5.3 OLT and ONUs Transmit Receive Structure

Both the OLT and ONU have a Transmit and receive component as shown in the diagram bellow. The first component, pseudo-random Binary Sequency (PRBS), generates Binary Bits to be transmitted to the ONU from the OLT & vice-versa. The Generated Bits are modulated using 8-PSK modulation i.e., each symbol represents 3 bits. To differentiate the upstream and downstream transmitted signal optical circulator is used. To further increase the data rate, we used dual polarization (Horizontal and vertical).

On the receiver side, polarizations are separated before detection. Signal on each polarization is detected by receiver after being filtered. Then the outputs go to DSP for distortion compensation and & decision component for decision on each received symbol based on normalized threshold settings. The PSK sequence decoder decodes PSK decoded signal. Finally parallel to serial converter is used to couple input sequences into one output sequence

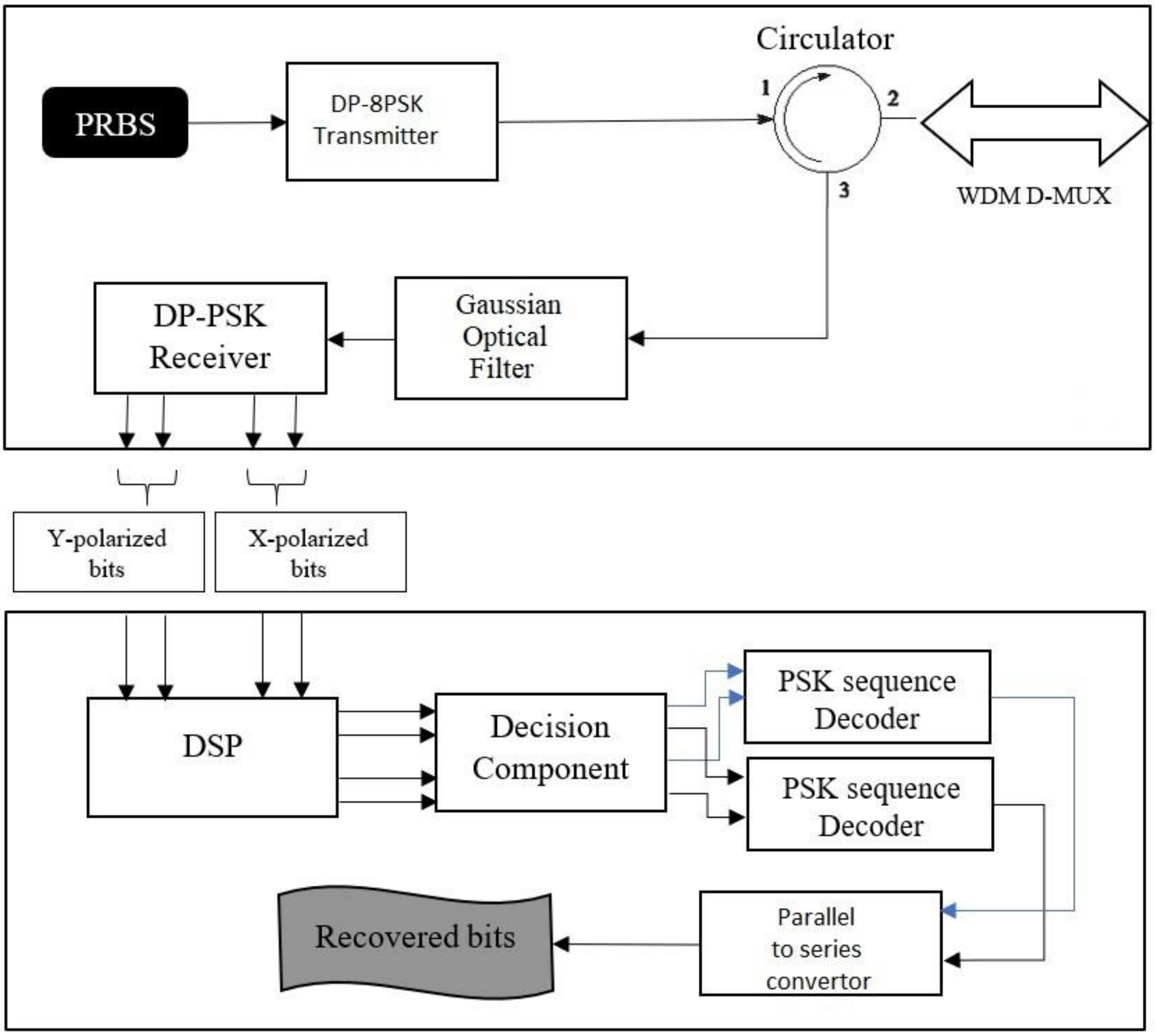


Figure 5-2 OLT and ONU have a Transmit and receive component

5.4 Transmit Receive Structure on Optisystem

5.4.1 Transmit Structure on Optisystem

The Transmit structure consists of a dual-polarization 8-PSK transmitter, polarization multiplexer, PSK modulator and polarization splitter.

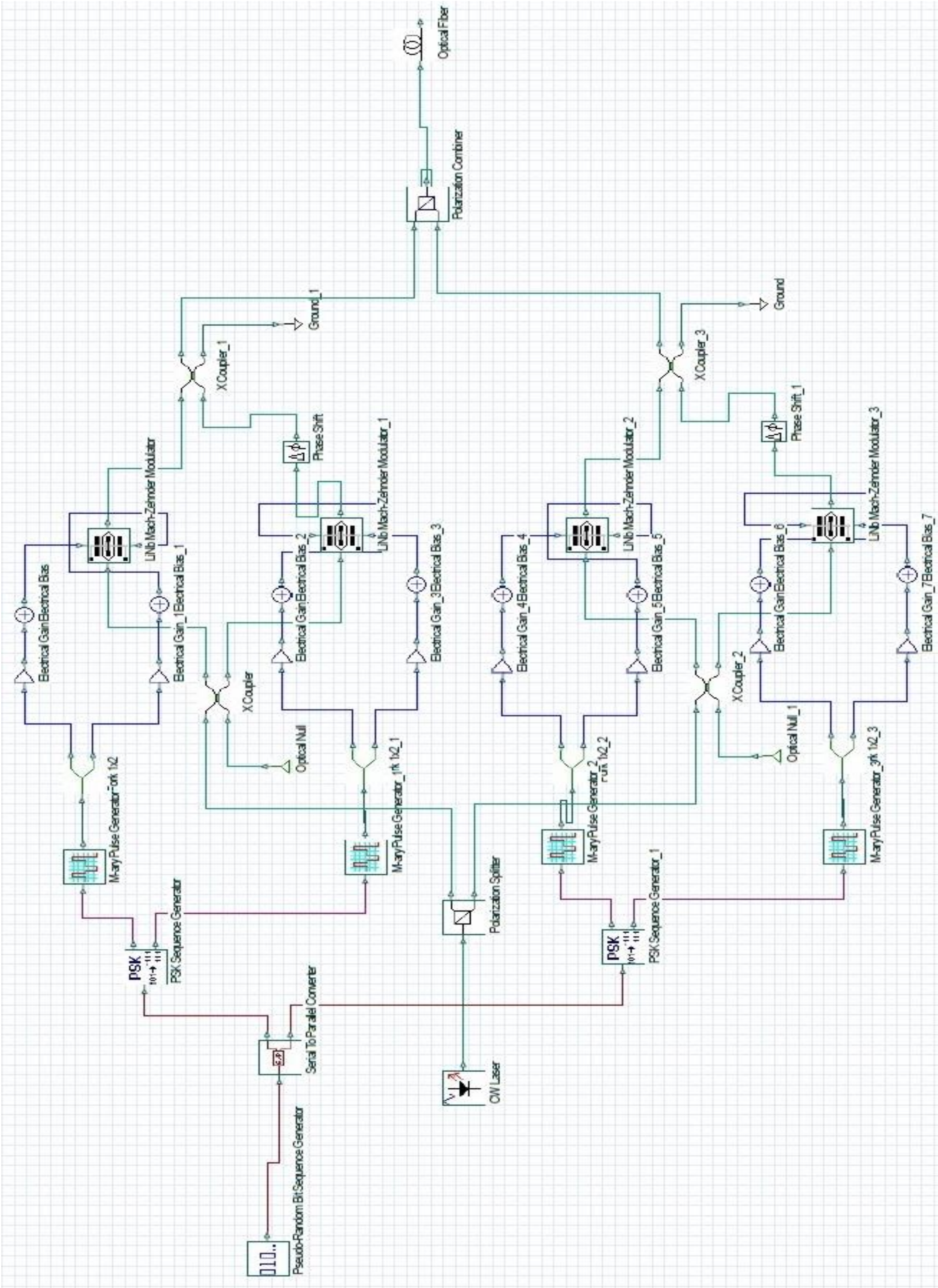


Figure 5-3 Transmit Structure on Optisystem

5.4.2 Receive Structure on Optisystem

The Receiver structure is a dual-polarization 8-PSK receiver with hetrodyne receiver design. It consists of a Local Osilator , Poloirization beam splitter , PSK demodulator .

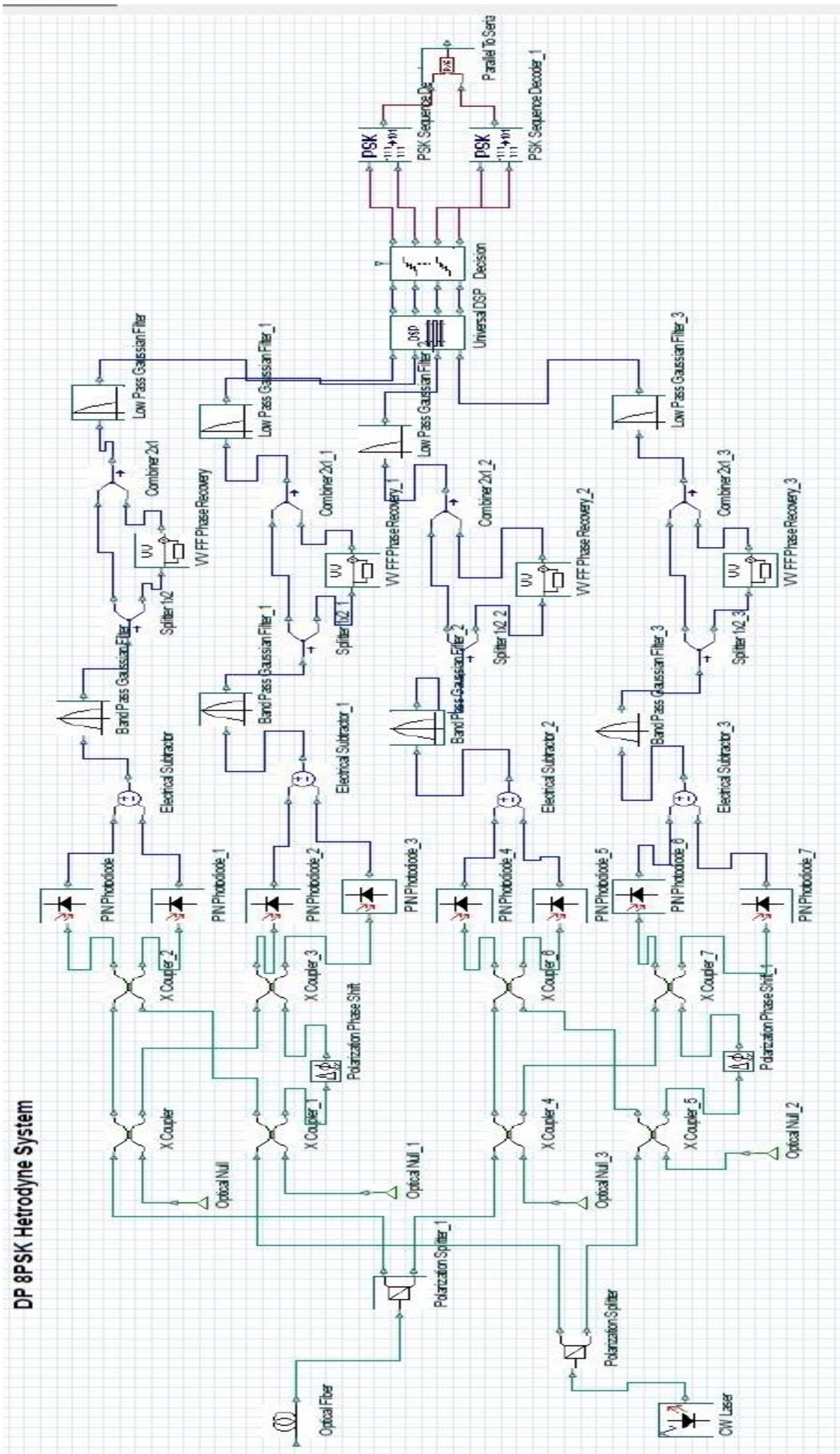


Figure 5-4 Receiver Structure on Optisystem

5.5 Parameters Used in the Simulation

5.5.1 Bit & Baud-Rate

The following table shows the bit rate, symbol rate, samples per bit used in the simulation. To achieve a data rate of 300 Gbps the symbol rate should be 50 G per second and the samples transmitted per bit since we use 8-PSK.

Parameter	Value Used	Unit
Bit Rate	300*10^9	Bits/sec
Symbol Rate	50*10^9	Symbols/sec
Samples per bit	3	-
Guard bits	100	

Table 5-2 Data Rate Parameters

5.5.2 WDM Multiplexer & De-multiplexer Parameters

The input PSK signals generated by the Transmitter & modulated using DP-8PSK modulator are multiplexed by using WDM-Multiplexer. The Signals are filtered by an optical filter and combined in one signal. The optical filter used is Gaussian optical filter.

Quantity	Device	Parameter	Value
1	WDM Multiplexer	Bandwidth	100 GHz
		Filter Type	Gaussian
		Channels	100

Table 5-3 WDM Multiplexer parameters

The received Signal (combined on the transmitter side) are split into their corresponding wavelength using WDM-demultiplexer. Then the output signals are filtered by a Gaussian optical filter.

Quantity	Device	Parameter	Value
1	WDM Demultiplex	Bandwidth	100 GHz
		Filter Type	Gaussian
		Channels	100

Table 5-4 WDM De-multiplexer parameters

5.5.3 PSK Transmitter

On Transmitter side, two QPSK Transmitters are in cascade used to implement 8PSK Transmitters. The QPSK signal is generated by using MZ modulators to encode the QPSK symbols onto an optical carrier. The frequencies used for the simulation are listed in table 5-5. Each modulator branch modulates the in-phase (I) and quadrature components (Q) of a carrier.

Quantity	Device	Parameter	Value (THz)
16	QPSK Tx	Frequency	194.95,194.90,194.85,194.80,194.75,194.70,194.65,194.60
			197.53,197.48,197.43,197.38,197.33,197.28,197.23,197.18

Table 5-5 QPSK Transmitter used frequencies

5.5.4 Filter

We used Gaussian optical filter. The Gaussian optical filter component is an optical filter with a Gaussian frequency transfer function. The frequencies used for the simulation are listed in table 5-6. The filter's center frequency is set according to the value in the table. The bandwidth is set to 100.

Quantity	Device	Parameter	Value (THz)
16	Gaussian Optical Filter	Frequency	197.53,197.48,197.43,197.38,197.33,197.28,197.23,197.18
			194.95,194.90,194.85,194.80,194.75,194.70,194.65,194.60
		Bandwidth	100

Table 5-6 Filter Centre frequencies

5.5.5 PSK Sequence Decoder

For the simulation we used 8PSK modulation, hence 3 bits per symbol are used in the coding. Since the phase of a signal is varied according to the source symbols when transmitting information, the symbols are decoded according to their corresponding phase mapping. The binary bit sequence is rebuilt from input subsequences.

Quantity	Device	Parameter	Value	Unit
32	PSK Sequence Decoder	Bits Per Symbol	3	Bits/symbol
		Phase Offset	45	Degree

Table 5-7 PSK Decoder parameters

5.6 Results and discussion

5.6.1 Wavelengths spectrum

Shown in the figure 5-5 and 5-6 are wavelength spectrums in uplink and downlink. Wavelengths allocated are captured before the power coupler in the uplink and after the WDM-Multiplexer in the downlink direction.

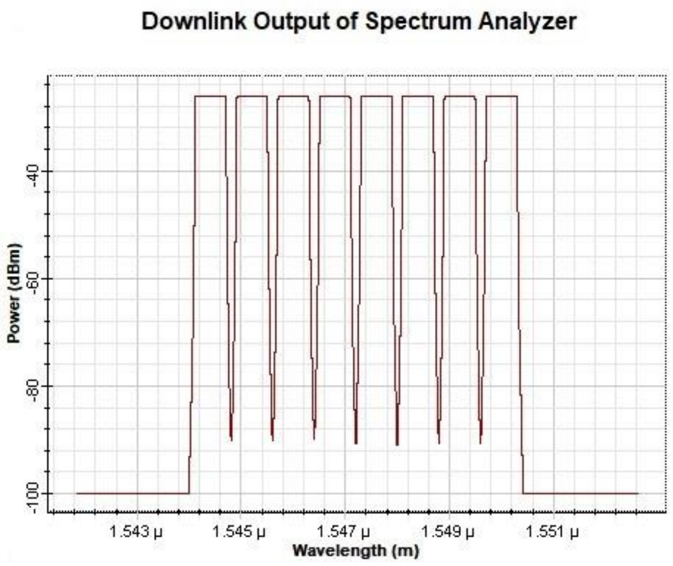


Figure 5-5 Spectrum Analyzer Output (Downlink)

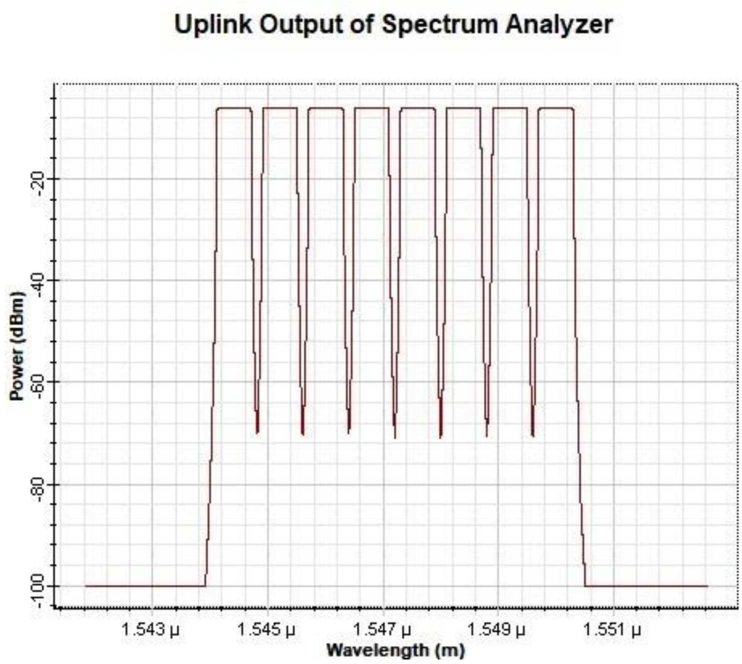


Figure 5-6 Spectrum Analyzer Output (Uplink)

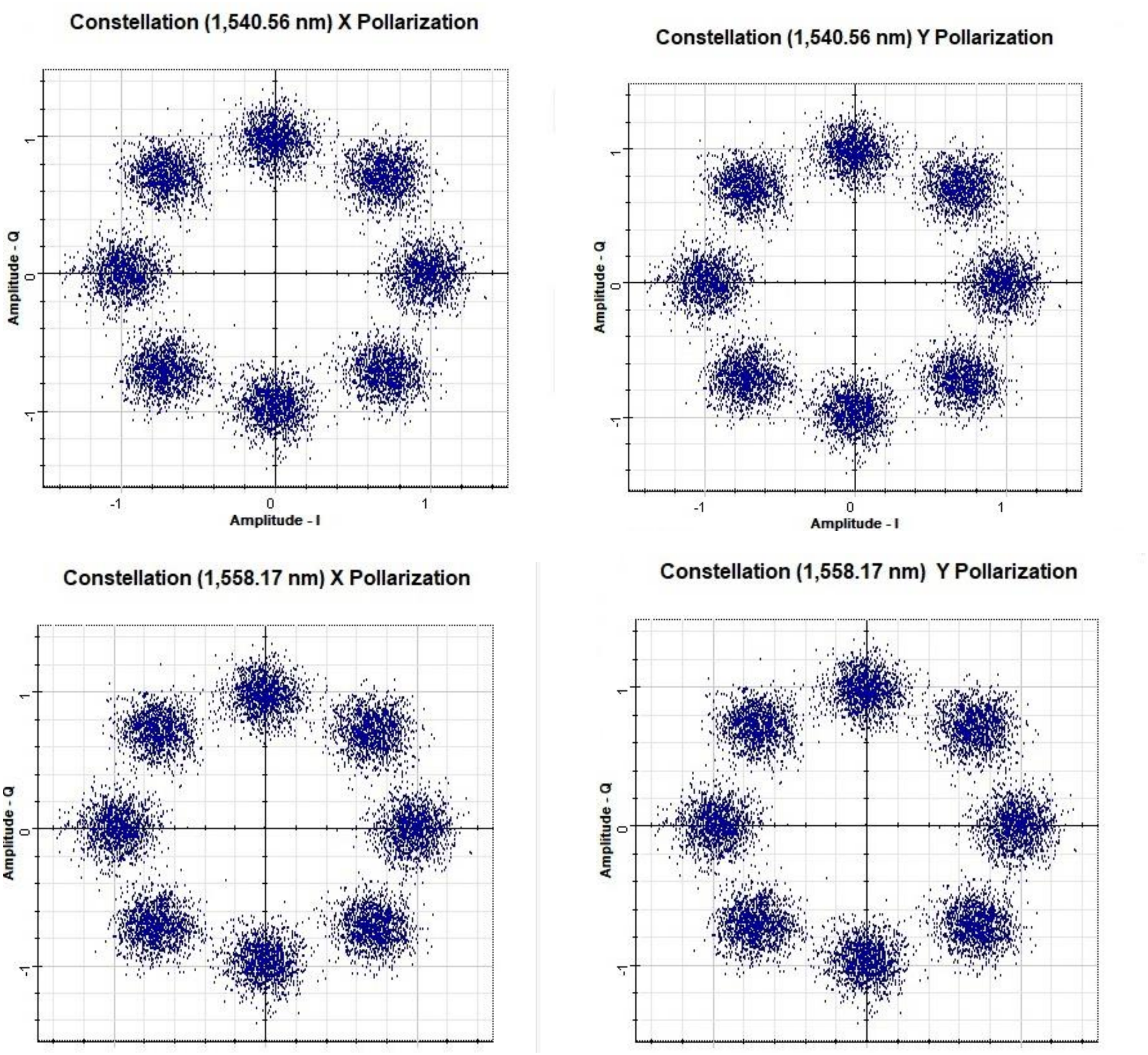
5.6.2 Constellation diagram

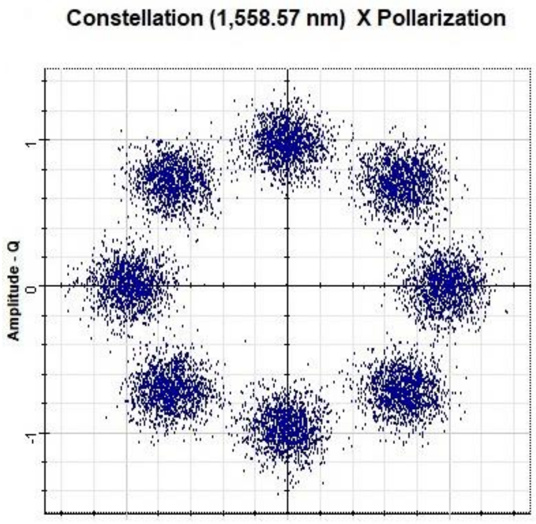
5.6.2.1 Constellation diagram of Heterodyne System

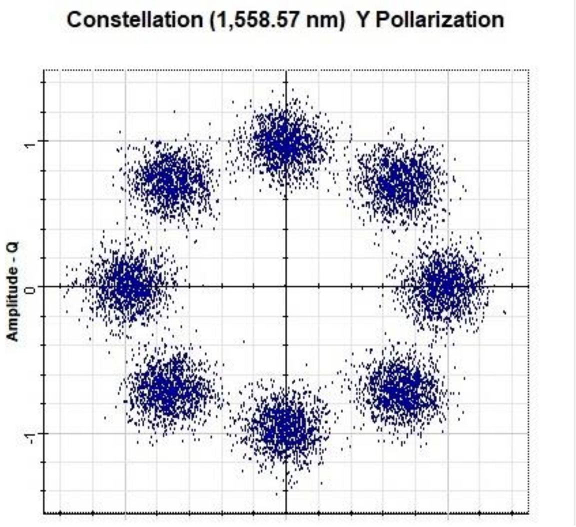
In this section, the constellation diagram of the eight uplink and eight downlink signals for both horizontal and vertical polarization found from the simulating proposed transmission system are shown and results are discussed.

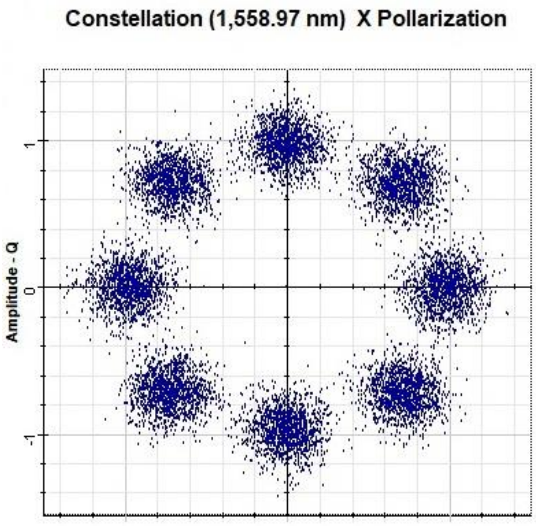
a) Downlink

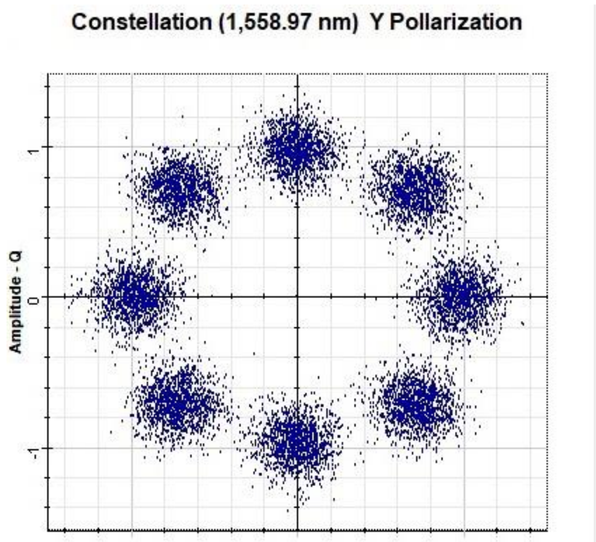
Horizontal and vertical polarization constellation diagrams are shown in figure 5.7 for downlink wavelengths λ9, λ10, λ11, λ12, λ13, λ14, λ15 and λ16 on left and right side respectively. As can be seen from the constellation diagram of the downlink wavelengths (from i.e., λ9-λ16), the constellation points surrounding each symbol position are far from each other. This indicates that there is not much interference and distortion that can cause a symbol error. Hence from the simulation results, we can conclude that error free transmission can be achieved.

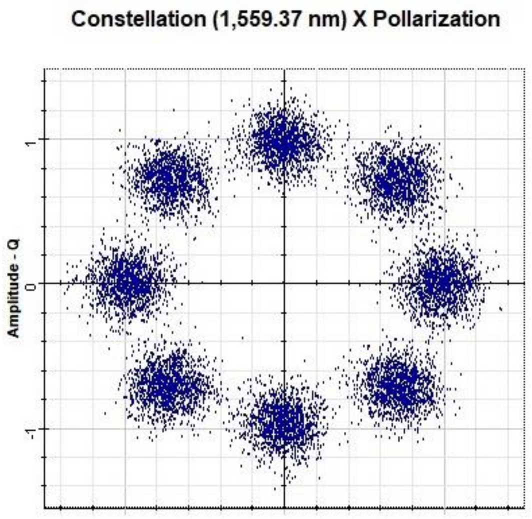


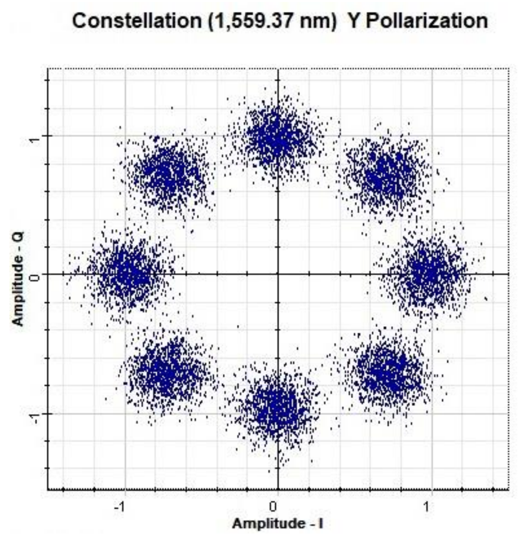

Constellation (1,558.57 nm) X Pollarization
Amplitude - Q
1
0
-1

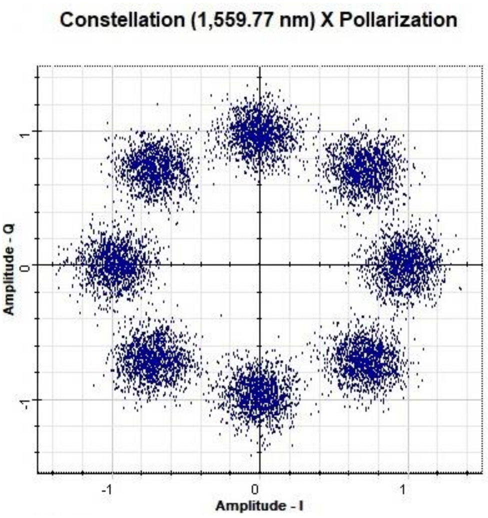

Constellation (1,558.57 nm) Y Pollarization
Amplitude - Q
1
0
-1

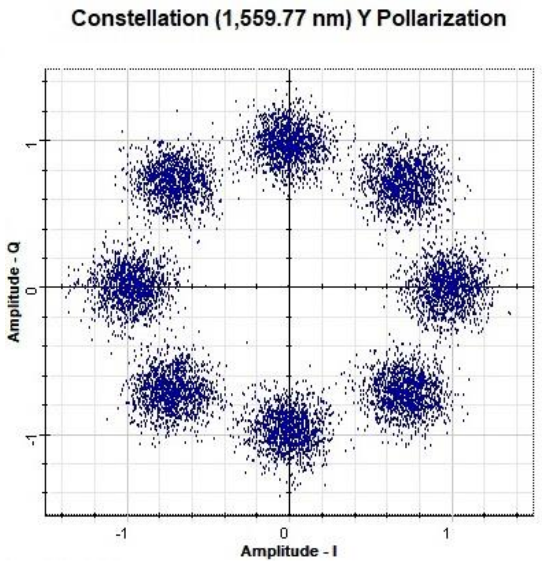

Constellation (1,558.97 nm) X Pollarization
Amplitude - Q
1
0
-1

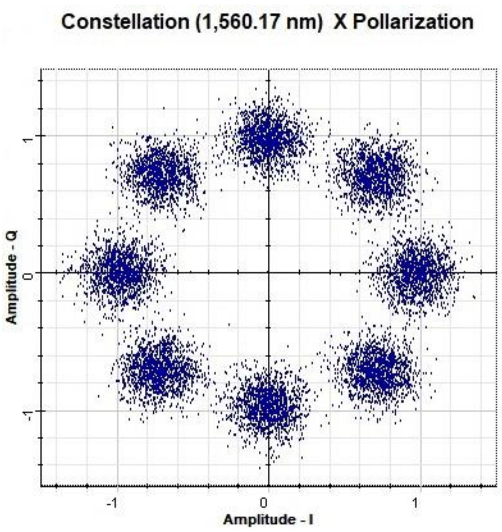

Constellation (1,558.97 nm) Y Pollarization
Amplitude - Q
1
0
-1

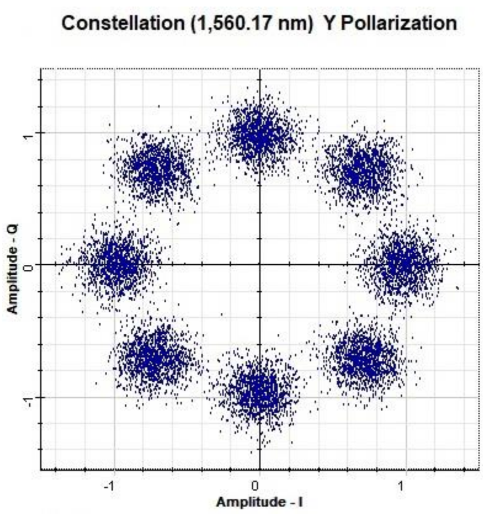

Constellation (1,559.37 nm) X Pollarization
Amplitude - Q
1
0
-1

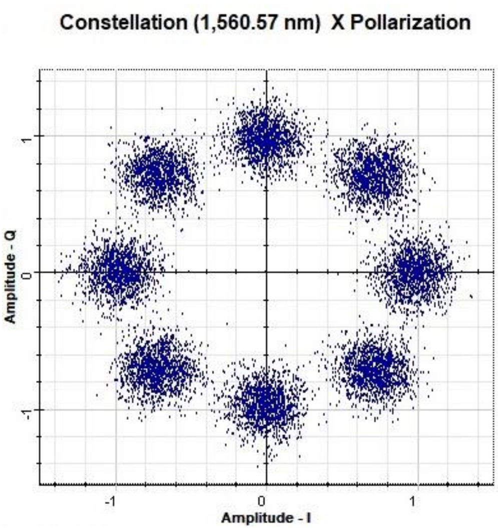

Constellation (1,559.37 nm) Y Pollarization
Amplitude - Q
1
0
-1
-1
0
1
Amplitude - I

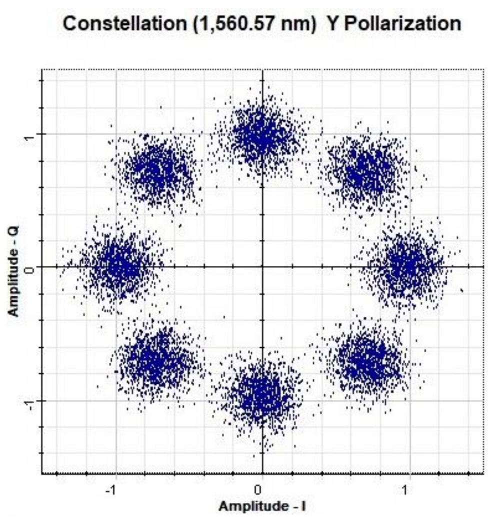

Constellation (1,559.77 nm) X Pollarization
Amplitude - Q
Amplitude - I


Constellation (1,559.77 nm) Y Pollarization
Amplitude - Q
Amplitude - I


Constellation (1,560.17 nm) X Pollarization
Amplitude - Q
Amplitude - I


Constellation (1,560.17 nm) Y Pollarization
Amplitude - Q
Amplitude - I


Constellation (1,560.57 nm) X Pollarization
Amplitude - Q
Amplitude - I


Constellation (1,560.57 nm) Y Pollarization
Amplitude - Q
Amplitude - I

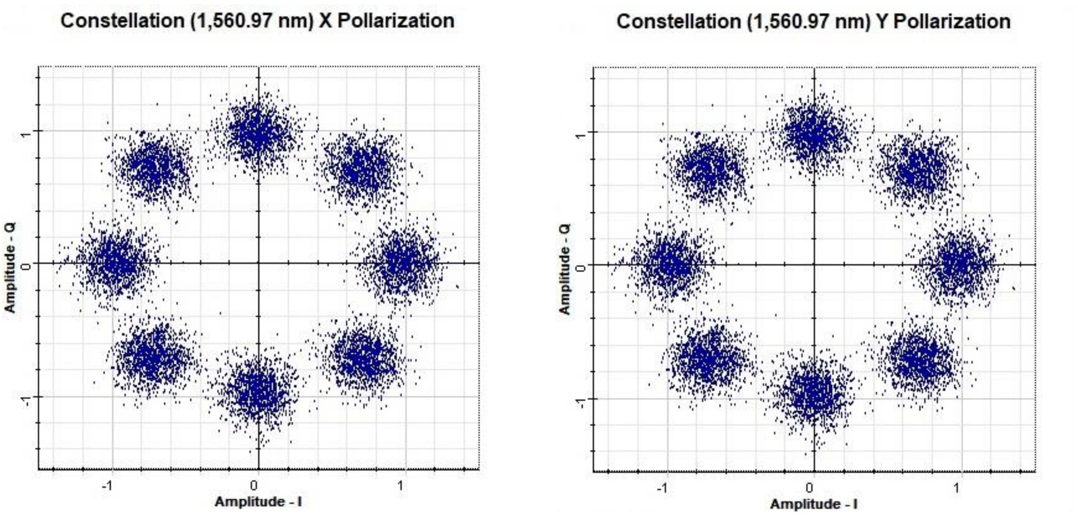
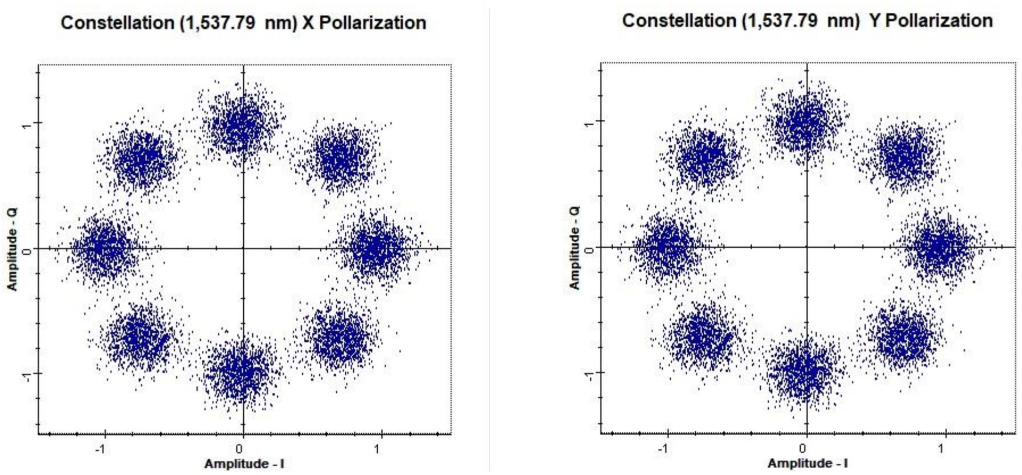


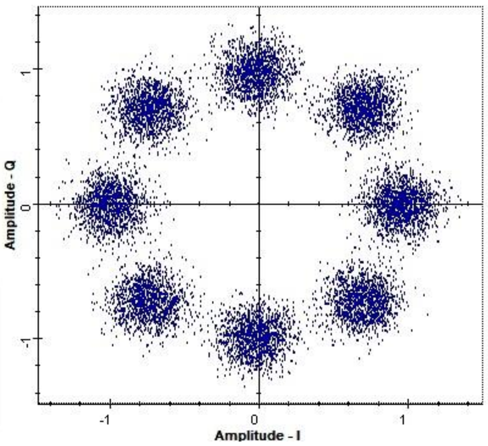
Figure 5-7 Constellation Diagram of Downlink signals for horizontal and vertical polarizations

b) Uplink

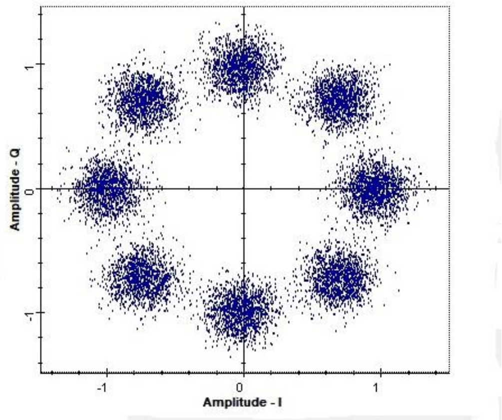
In figure y.x , Horizontal and vertical polarization constellation diagrams are shown for downlink wavelengths λ1, λ2, λ3, λ4, λ5, λ6, λ7, and λ8 on left and right side respectively. As can be seen from the constellation diagram of the downlink wavelengths, the constellation points surrounding each symbol position are far from each other. This indicates that there is not much interference and distortion that can cause a symbol error. From the constellation diagram, we can conclude that, error free transmission can be achieved for the uplink wavelengths too.



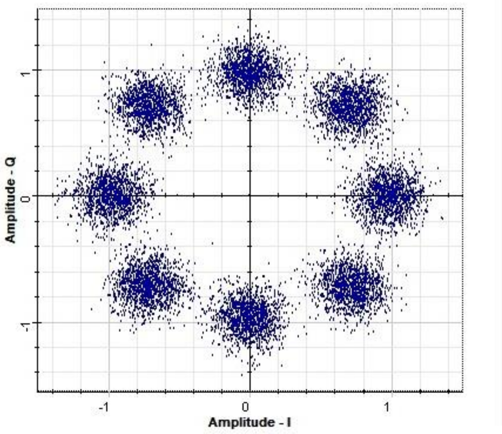
Constellation (1,538.19 nm) X Pollarization



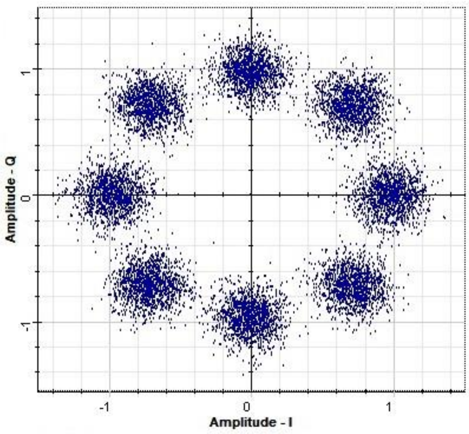
Constellation (1,538.19 nm) Y Pollarization



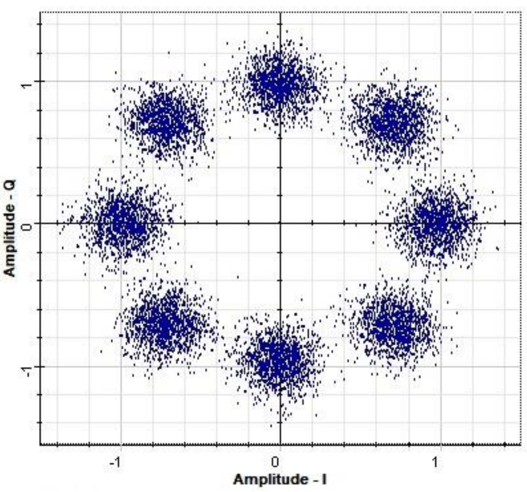
Constellation (1,538.58 nm) X Pollarization



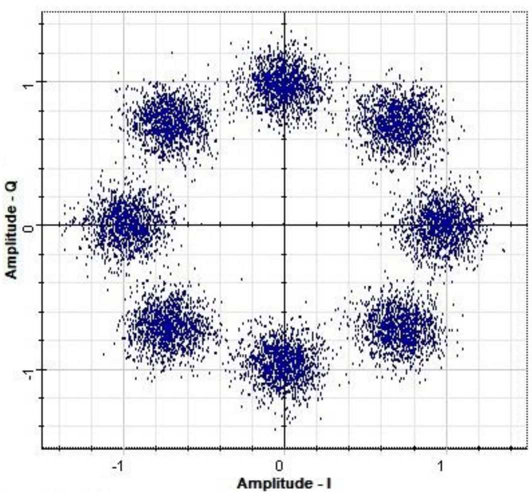
Constellation (1,538.58 nm) Y Pollarization



Constellation (1,538.98 nm) X Pollarization



Constellation (1,538.98 nm) Y Pollarization



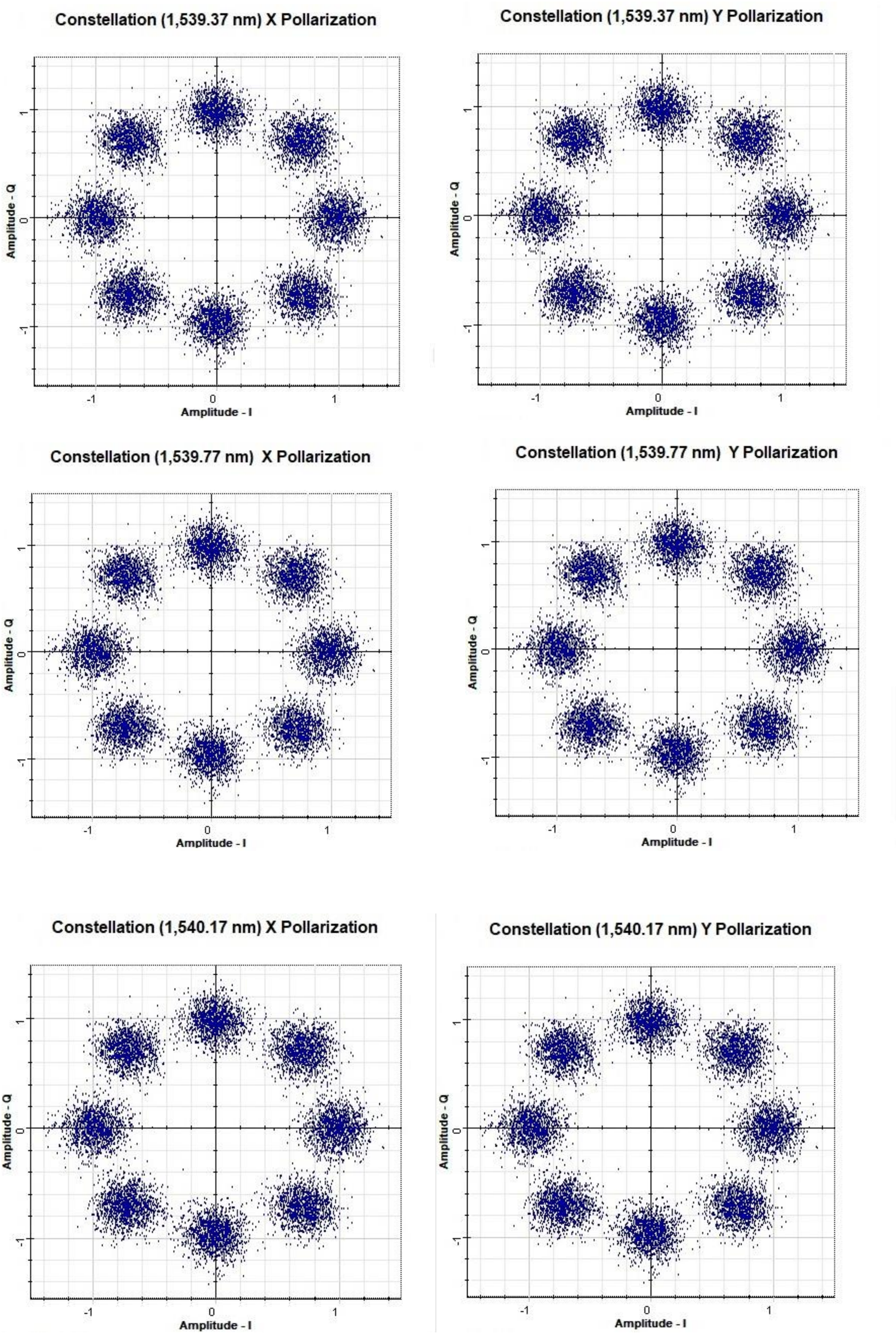


Figure 5-8 Constellation Diagram of Uplink signals for horizontal and vertical polarizations

5.6.2.2 Constellation diagram of Back-to-Back System

For the back-to-back model simulation, the first downlink wavelengths (i.e.,1,558.17) is used. The constellation diagrams bellow show simulation results in vertical and horizontal polarizations. From the constellation diagram, points surrounding each symbol position are far from each other which indicates that there is not much interference and distortion that can cause a symbol error. Hence, we can conclude that error free transmission can be achieved.

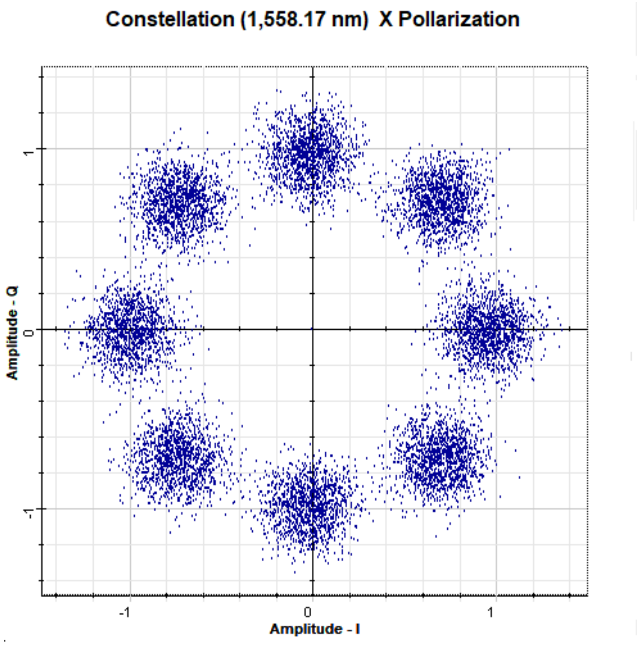


Figure 5-9 Constellation Diagram of X polarizations for 1,558.17 nm

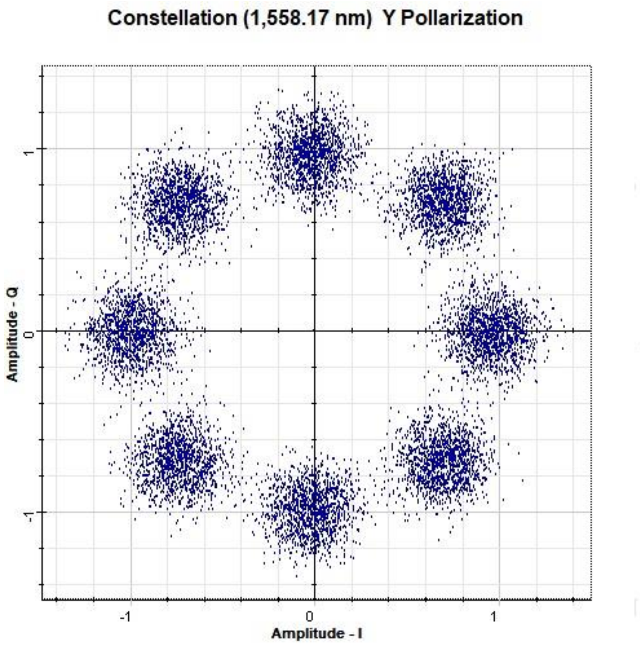


Figure 5-10 Constellation Diagram of Y polarizations for 1,558.17 nm

5.6.3 OSNR and BER Result

5.6.3.1 OSNR and BER of Heterodyne System

The following tables show the OSNR Vs BER Results of each wavelength both for Downlink and Uplink. Table 5-8 and figure 5.11 show the variation of the BER with respect to input signal OSNR. The experimental results obtained for the eight downlink wavelengths (λ9, λ10, λ11, λ12, λ13, λ14, λ15, λ16) are plotted in the table and plotted the figure. We observed that the wavelengths have similar performance. As can be seen from the figure, an OSNR of 15.5 dB is required to obtain a BER of -3 (log) or 10^{-3} dB. BER decreases sharply beyond OSNR of 16 dB with a slight increase of OSNR, for OSNR of 17 dB, the BER is 10^{-4} and for 18 dB it is 10^{-5}.

OSNR(dB)	λ9	λ10	λ11	λ12	λ13	λ14	λ15	λ16
9	-0.230	-0.157	-0.155	-0.083	-0.152	-0.151	-0.136	-0.132
10	-0.694	-0.640	-0.640	-0.586	-0.639	-0.640	-0.623	-0.623
11	-1.157	-1.123	-1.125	-1.089	-1.128	-1.123	-1.114	-1.112
12	-1.844	-1.863	-1.863	-1.882	-1.861	-1.857	-1.864	-1.863
13	-2.208	-2.166	-2.166	-2.123	-2.169	-2.164	-2.152	-2.152
14	-2.433	-2.467	-2.465	-2.501	-2.460	-2.456	-2.466	-2.469
15	-2.736	-2.816	-2.817	-2.896	-2.820	-2.814	-2.826	-2.830
16	-3.258	-3.253	-3.252	-3.247	-3.249	-3.248	-3.240	-3.238
17	-3.700	-3.835	-3.836	-3.970	-3.840	-3.828	-3.861	-3.866
18	-4.900	-5.000	-4.998	-5.100	-4.991	-4.991	-5.010	-5.016

Table 5-8 OSNR vs BER Result in Downlink

Figure 5-11 Variation of BER with OSNR

Table 5-9 and figure 5-12 show the variation of the BER with respect to input signal OSNR for the uplink . The experimental results obtained for the eight uplink wavelengths (λ1, λ2, λ3, λ4, λ5, λ6, λ7, and λ8) are plotted in the table and plotted the figure. We observed that the wavelengths have also similar performance. As can be seen from the figure, an OSNR of 16 dB is required to obtain a BER of -3 (log) or 10^{-3} dB. BER decreases sharply beyond OSNR of 16 dB with a slight increase of OSNR, for OSNR of 17, the BER is $10^{-3.5}$ and for 18 it is 10^{-5} .

OSNR(dB)	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
9	-0.172	-0.251	-0.248	-0.330	-0.250	-0.270	-0.274	-0.281
10	-0.620	-0.683	-0.676	-0.745	-0.681	-0.696	-0.700	-0.705
11	-1.069	-1.115	-1.113	-1.160	-1.114	-1.126	-1.128	-1.132
12	-1.766	-1.774	-1.765	-1.781	-1.771	-1.773	-1.772	-1.774
13	-2.016	-2.014	-2.007	-2.011	-2.012	-2.011	-2.010	-2.011
14	-2.315	-2.343	-2.336	-2.371	-2.341	-2.348	-2.349	-2.352
15	-2.670	-2.665	-2.660	-2.660	-2.664	-2.662	-2.662	-2.662
16	-3.060	-3.032	-3.023	-3.003	-3.029	-3.022	-3.019	-3.018
17	-3.490	-3.454	-3.449	-3.417	-3.452	-3.443	-3.440	-3.438
18	-4.720	-4.615	-4.610	-4.510	-4.614	-4.587	-4.580	-4.573

Table 5-9 OSNR vs BER Result in Uplink

Figure 5-12 Variation of BER with OSNR

5.6.3.2 OSNR and BER of Back-to-Back System

In Table 5-10 and figure 5-13 are shown the variation of the BER with respect to input signal OSNR for Back-to-Back Fiber System. The experimental results obtained for the selected wavelength (i.e., λ9) is listed in the table and shown in figure. An OSNR of 15 dB is required to obtain a BER of -3 (log) or 10^{-3} dB. With a slight increase in OSNR beyond 17, the BER decreases sharply, for OSNR of 17, the BER is around 10^{-4} dB and for 18 dB it is 10^{-5} dB.

OSNR(dB)	BER (dB) ,λ9
9	-0.073
10	-0.597
11	-1.132
12	-1.879
13	-2.238
14	-2.632
15	-3.122
16	-3.603
17	-4.229
18	-5.212

Table 5-10 OSNR vs BER of Back-to-Back System

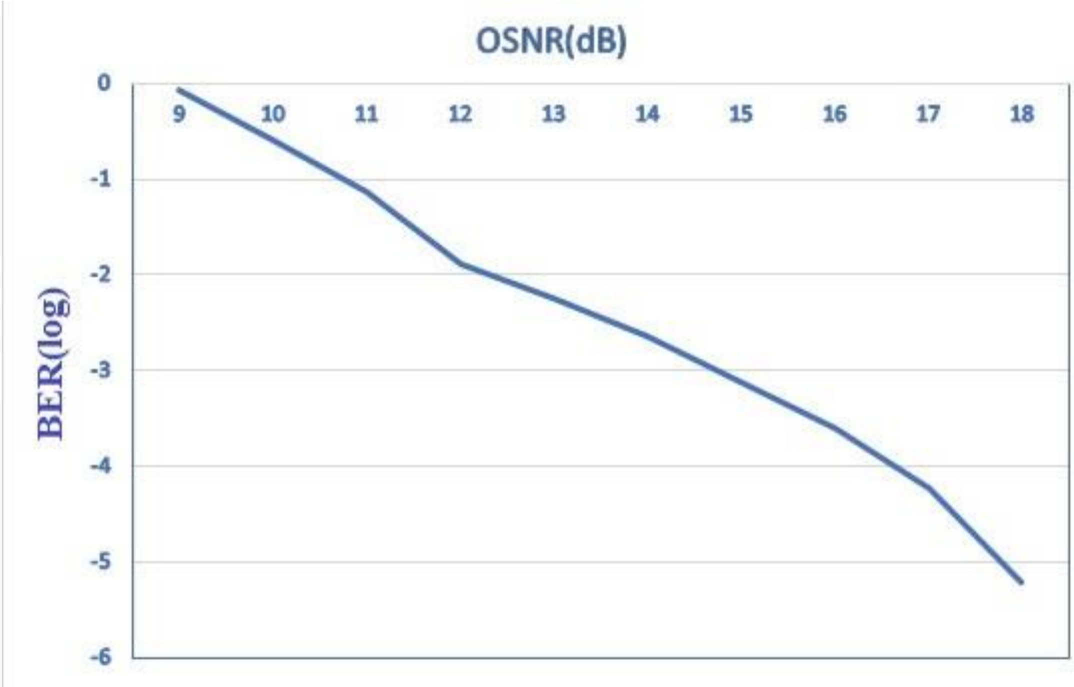


Figure 5-13 Variation of BER with OSNR for B2B

5.6.3.3 BER Comparison of Heterodyne and Back-to-Back System Results

For the comparison of Heterodyne system and Back-to-Back system, the wavelength λ9 is selected. Table 5-11 show BER for a given OSNR in dB and figure 5-14 variation of BER with input signal OSNR. The BER results obtained from the Heterodyne system simulation are very close to the result found in case of back-to-back system. An OSNR of 15.4 is required to obtain a BER of -3 (log) or 10−3 dB for Heterodyne System while an OSNR of 14.8 dB is required for Back-to-Back System which is 0.6 dB higher. For input signal OSNR values higher than 16 both Heterodyne and Back-to-Back system BER values decrease sharply. The heterodyne system has slightly higher BER value as compared to Back-to-back system due to dispersion and nonlinear effects of the fiber.

	Heterodyne	Back-to-Back
OSNR (dB)	BER (dB), λ9	BER (dB), λ9
9	-0.230	-0.073
10	-0.694	-0.597
11	-1.157	-1.132
12	-1.844	-1.879
13	-2.208	-2.238
14	-2.433	-2.632
15	-2.736	-3.122
16	-3.258	-3.603
17	-3.700	-4.229
18	-4.900	-5.212

Table 5-11 BER Comparison of Heterodyne and Back-to-Back System Results

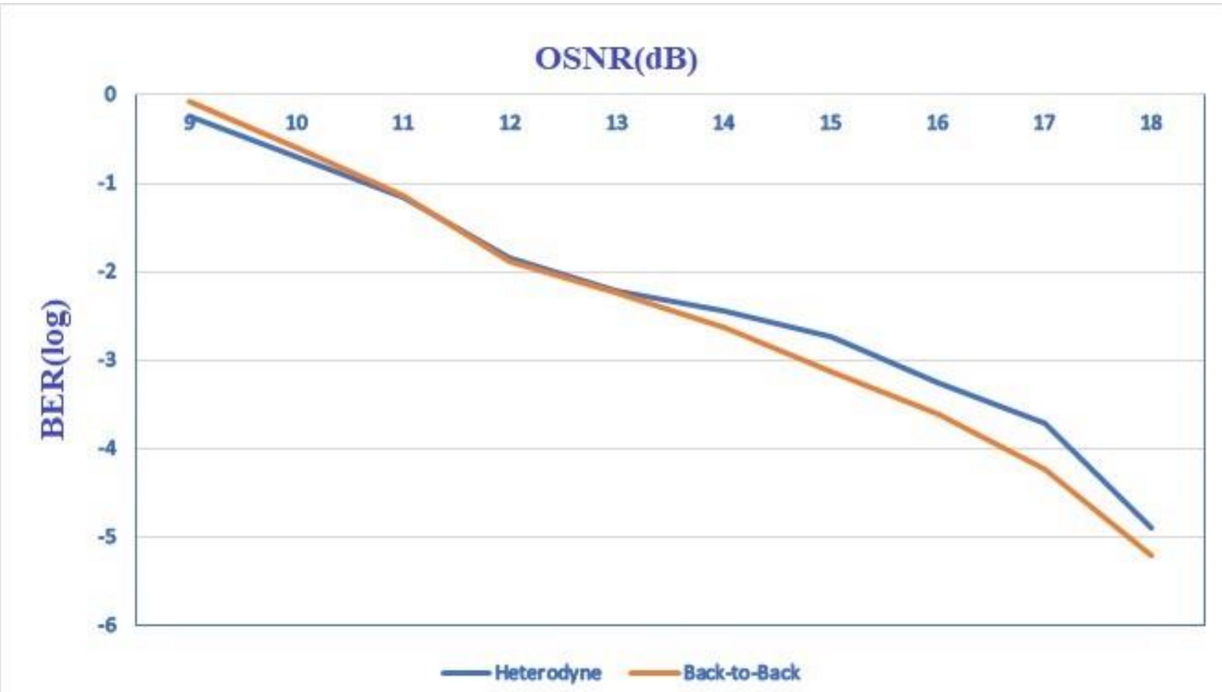


Figure 5-14 Comparison of BER vs OSNR

Chapter Six

6 Conclusions and Future Work

6.1 Conclusions

In this thesis a total capacity of 2.4 Tbps data rate using eight wavelength pairs or 300 Gbps data rate per channel was obtained. The System model, General architecture of the system, transmitter and receiver structure used to test the proposed system were discussed thoroughly. For the simulation, DP-8PSK transmitters were used on the transmitter side while on the receiver side heterodyne DP-8PSK receiver was used. Comparison of simulation results between coherent WDM DP-8PSK PON with heterodyne receiver and back-to-back fiber system using BER showed a very close performance. From the result, we can conclude that, the proposed coherent WDM Dual Polarization 8-PSK PON system with heterodyne receiver can be used in 5G transmission network despite a dispersion and other nonlinear effects which cause insignificant loss.

6.2 Future Work

The scope of this thesis was to design a transmission system which can serve a total data rate of 2.4 Tbps or 300 Gbps per channel using heterodyne receiver. The thesis considered PSK modulation technique since it has higher sensitivity compared to ASK & FSK modulation techniques. Furthermore, the transmission system was tested using a simulation software.

The thesis can be further extended to the following areas.

- Testing the system on hardware
- Using different variants of PSK modulation techniques such as Offset QPSK (OQPSK), shaped-offset QPSK and π/4-QPSK

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