PERFORMANCE ENHANCEMENT OF BACKWARD COMPATIBLE NGPON2/GPON SYSTEMS

A Thesis Submitted in Fulfillment of the Requirement for the Award of the Degree of

MASTER OF ENGINEERING

In Electronics and communication

Submitted By

Dhruva Sharma

801661029

Under Supervision of

Dr. Sanjay Sharma
PROFESSOR

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR INSTITUTE OF ENGINEERING & TECHNOLOGY

(DEEMED TO BE UNIVERSITY), PATIALA, PUNJAB

JULY, 2018

DECLARATION

I, ***Dhruva sharma*** *hereby declare that the work presented in this thesis entitled "***Performance Enhancement of Backward Compatible NGPON2/GPON Systems***" in fulfillment of the requirement for the award of degree of Master of Engineering (ECE) submitted at Electronics and Communication Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be university), Patiala is a record of genuine and independent project work done by me carried under the supervision of* ***Dr. Sanjay Sharma*** *(Professor, Electronics and Communication Engineering, TIET, Patiala) from January 2018 to June 2018. The work contained in this report has not been previously submitted to meet the requirements for a degree at this or any other higher educational institution.*

Date:13-07-2018

Dhruva Sharma
801661029

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

Date: 13-07-2018

Dr. Sanjay Sharma
(Professor)

CERTIFICATE

It is certified that the work contained in the thesis entitled **"Performance Enhancement of Backward Compatible NGPON2/GPON Systems"** by **Dhruva Sharma, 801661029** has been carried out under my supervision and that this work has not been submitted elsewhere for any other degree.

Dr. Sanjay Sharma
Professor
Electronics and Communication Engineering Department
Thapar Institute of Engineering & Technology
(Deemed to be University), Patiala, Punjab

Date:*13-07-2018*

ACKNOWLEDGEMENT

I would have never accomplished in completing my thesis work without the cooperation, encouragement and assistance provided by various people. I have no words to describe my deepest regards. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through this entire task. I acknowledge with gratitude to **Dr. Sanjay Sharma**, **Professor**, Electronics and Communication Engineering Department, Thapar University, Patiala, under whose guidance I had privilege to complete this thesis. I wish to express my honor towards him for providing individual guidance and constant support throughout the dissertation work.

I convey my sincere thanks to **Head of department, Dr. Alpana Agarwal** as well as **PG Coordinator, Dr. Ashutosh Kumar Singh, Assistant Professor,** Electronics and Communication Engineering Department, entire faculty and staff of Electronics and Communication Engineering Department for their kind encouragement and cooperation.

I am thankful to all who wished me success, especially my parents. Above all I render my gratitude to the Almighty who bestowed self-confidence, ability and strength to maintain my progress in track. I have no valuable words to express my thanks, but my heart is still full of the favours received from each and everyone.

Dhruva Sharma

801661029

ABSTRACT

Passive optical networks are getting attention of the researchers because of large number of benefits given by these systems. But, till date, work of the upgradation of conventional PON standards by integrating existing PONs with latest high speed standards are reported very less. More specifically, back compatibility and integration of NGPON2 and GPON is an interesting task for upgrading the existing standard to high bit rates for the fulfilment of ever increasing requirements of end users. It provide the benefits of pay as you grow and also this joint operation of NGPON2 and GPON provides the cost effectiveness and saves the strands of fiber by upgrading the conventional already deployed systems.

Time and wavelength division based PON is a groundbreaking technology in the field of access networks and an essential driver for NGPON2 (next generation passive optical network). In this work, a backward compatible integrated TWDM PON and Gigabit PON is demonstrated by incorporating mode division multiplexing. Video overlay is also considered in this work along with back compatibility of PON standards. Cost efficient and reliable system is proposed as required in next generation access networks. Data, audio and video are sent over TWDMPON/GPON and diverse linear polarized modes are analyzed. Proposed system is a new approach for the pay as you grow services. This is a promising integration of two diverse standards that can work on same feeder fiber or ODN without any extra deployment of fiber. Q factor along with BER is evaluated in the system for different link lengths, and different intensity profiles i.e. LP mode profiles. It is evident that TWDM PON is better than GPON and odd LP mode provides better performance in both PON standards. It is observed that NGPON2 performs better than GPON in terms of Q factor and BER. Further analysis of different LP mode profiles in proposed system has been done and it is evident that LP11 mode performs best and LP12 performs worst. Therefore, proposed system is enhanced in performance, cost efficient, uses same ODN, reliable for the future generation networks.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

)

LIST OF GLOSSARY

GPON	*Gigabit Passive Optical Network*
MDM	*Mode division multiplexing*
ONU	*Optical Network Unit*
FTTH	*Fiber To The Home*
LP	*Linearly polarized*
MZM	*Mach-Zehnder Modulator*
OLT	*Optical Line Terminal*
ODN	*Optical Distribution Network*
FTTC	*Fiber To The Curb*
CO	*Central Office*
TDM	*Time Division Multiplexing*
WDM	*Wavelength Division Multiplexing*
RN	*Remote Node*
NRZ	*Non-Return to Zero*
OCDMA	*Orthogonal Frequency Division Multiplexing*
SAC	*Spectral Amplitude Coding*
DDW	*Diagonal Double Weight*
MD	*Multi-Diagonal*
IM	*Intensity Modulator*
PD	*Photo-Detector*
LPF	*Low Pass Filter*

BER	*Bit Error Rate*
OFC	*Optical Fiber Communication*
BPON	*Broadband Passive Optical Network*
APON	*ATM Passive Optical Network*
EPON	*Ethernet Passive Optical Network*
SNR	*Signal to Noise Ratio*

CHAPTER 1

INTRODUCTION

1.1 OPTICAL FIBER COMMUNICATION

Information technology is the prime requirement of the mankind nowadays and communication remains an important part of the society throughout its history. For the accomplishing the information exchange in historic times, diverse approaches were employed such as communication through birds, through smoke etc. As the time passes on, technology also improved and information exchange between two points becomes simpler then former days. Electrical cable medium are incorporated for the data transmission such as copper cables and co-axial cables. There is simultaneous happening phenomenon such as there is development of the communication as well as population increase. Due to the explosive increase in the population, pressure is observed on the transmission mediums. Bandwidth hunger increased and is increasing day by day. Electrical cable mediums posses less bandwidth and therefore provide low speed and low capacity. With the invention of a optical medium for transmission i.e. optical fiber, a pragmatic and ground breaking changes are experienced in the data transmission [1]. In these days, fiber optic dependent transmission is becoming an inevitable part of the communication networks because of having the potential to serve the high speed networks and can cover prolonged transmission distances. Fiber optic medium was not that easily developed as it assumed to be and in the early days of the enhancement of the technology, it suffered from the losses of 1000 dB/km for distance of a kilometre. It was not incorporated in the commercial applications due to these high attenuations. However, researchers were worked on the technology and due to their enormous bandwidth, were successful to manufacture an optical fiber with very low data rate (typically 0.2 dB/km). Multi-terabit systems are using a fiber optic in the systems because of very low attenuation relative to copper cables. Optical technology emerged with the numerous advantages and knocked the doors of the world by providing reliable transmission. OFC (optical fiber communication) has great potential to uphold robust conditions, ability to cater the high speed application, competence to handle asynchronous data traffic and great response to various channels multiple access techniques.

Broadband access networks using fiber optic are major attention for giving pioneering systems for the ever increasing demands [2].

Passive Optical Networks (PONs) lead over the other access networks for offering rapid data transmission to the prolonged link lengths with less cost expenditure to the customer's end [3]. Diverse techniques for multiplexing are used for the transmission purposes such as Time division based multiplexing, Optical codes division multiplexing and different wavelengths based multiplexing. Also researches nowadays are accentuating to get additional advantages of the multiplexing by joining two techniques such as WDM/TDM or OCDMA/WDM. To accomplish the considered necessary data at rapid rate, networks should be competent of successfully and efficiently using the available bandwidth. Also should have the potential or ability to hold system powerfully all the operation for example wavelength multiplexing, separation of the channels according to their specific transmitter pots i.e. de-multiplexing, channel splitting, adding & dropping wavelength, amplification etc. [5]. Besides the numerous benefits of the fiber optic, it has some disadvantages also such as costly components and high deployment cost. But once these installed, their maintenance is easy as compared to other mediums. Researcher continuously worked on the optimal employment of the fiber between sender or central office and receiver. In order to lower the cost of the optical networks, researchers invented various technologies like fiber to the hoe, fiber to the curb etc. A representation of fiber optic based communication is depicted in Figure 1.1.

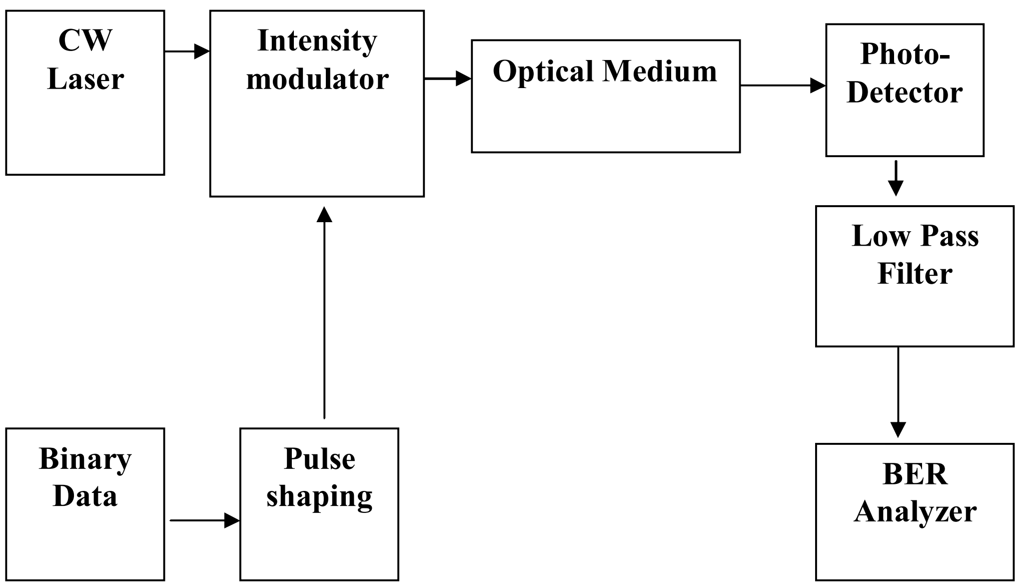


Figure 1.1 Block diagram of optical communication system

1.2MULTIPLE ACCESS TECHNIQUES

Multiple access is a method that allow diverse users to be operated under the same transmission medium and share the available bandwidth in the efficient way. Spectrum is restricted and in order to use it effectively, sharing among the different users is a utmost necessary. This accomplishes by allowing multiple users simultaneously and provides them bandwidth which is offered by the medium. Asynchronous and Synchronous are the major two types of this technique. Former technique is elaborated as the systems where information communication is not at constant rate i.e. it varies and because of this, inside the medium while transmission, collisions happens. However, in this method of transmission, data latency or delay is a major limitation. Now in later case, on the other hand, total signal transmission is perfectly fixed or scheduled and this results into reliable transmission as compared to the former technique [5].

The major multiple access protocols are:

1. Wavelength division multiple access (WDMA).
2. Time division multiple access (TDMA).
3. Code division multiple access (CDMA).

1.2.1 Requirement of Multiplexing

It is perceived that bandwidth of the mediums which are incorporated for the communication is very wide but due to employing only single transmitter as well as corresponding receiver, it gets wasted. Bandwidth can be shared between diverse multiple users. Utilization of the available bandwidth of transmission medium is termed as the multiplexing.

1.2.2 Principle

Basic block diagram of operation of packing diverse channels into one medium is illustrated in Figure 1.2. Multiple transmitters and their power is accumulated with help of multiplexer and fed to medium of communication. These "n" no. of signals after medium send to channel separator often termed as DEMUX. Basic function of this separator is to split the channels according to the transmitter ports so that each user get the authentic information. Therefore, it is a method to load large channels or to enhance the capacity of the system at the same instant of time inside same available bandwidth of the medium. These systems are getting more and more attention because of the ever increasing data requirements.

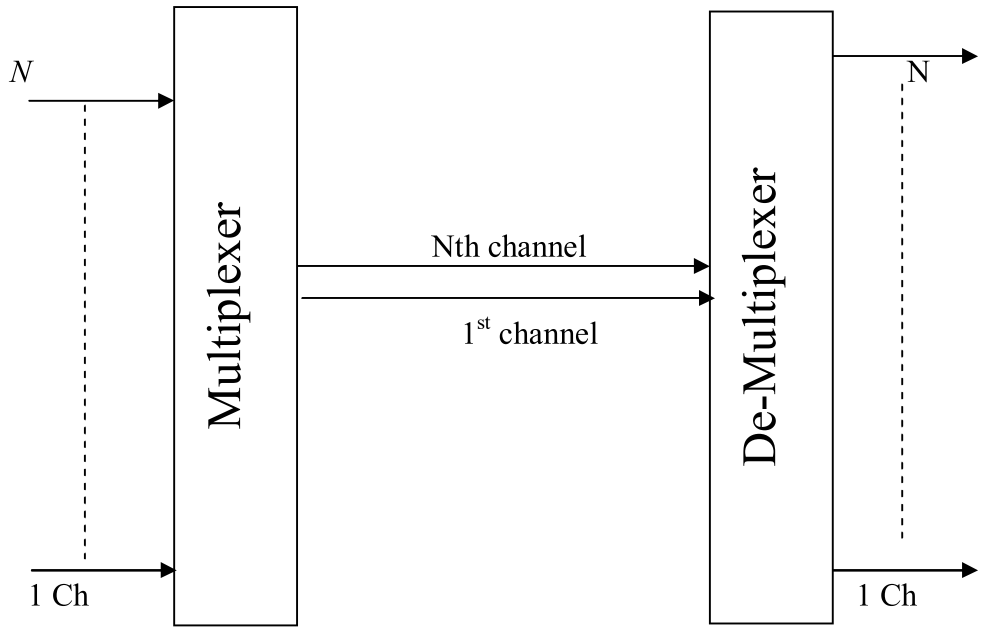


Figure 1.2 Block diagram of basic multiplexing

1.2.3 Wavelength Division Multiple Access

It is basically a system capacity enhancement technique which packs large number of channels into a single transmission medium. This can be operational in analog or can be used in the digital signal communications. Most of the uses was done in the analog due to the numerous benefits. In WDMA, it allows diverse users at diverse wavelengths to be operated under the same transmission medium (it can be electrical or optical) and share the available bandwidth in the efficient way for providing high capacity. Wavelength grid or window of spectrum is restricted and in order to use it effectively, sharing among the different users is an utmost necessary by multiplexing it with propose frequency spacings. This is a parallel channels communication and is different from the serial which used in time division.

For the distinguishing in the diverse multiple channels, a channel separation is required and this channel separation is not used for information transmission but only present to avoid interference between channels. However, this channel separation wastes the effective bandwidth. Major benefit of this multichannel multiplexing is the utilization of available spectrum to augment the capacity by incorporating wavelengths of different windows and it provide the freedom to pack any number of channels unless wavelength grid is optimal to use in the communication [6].

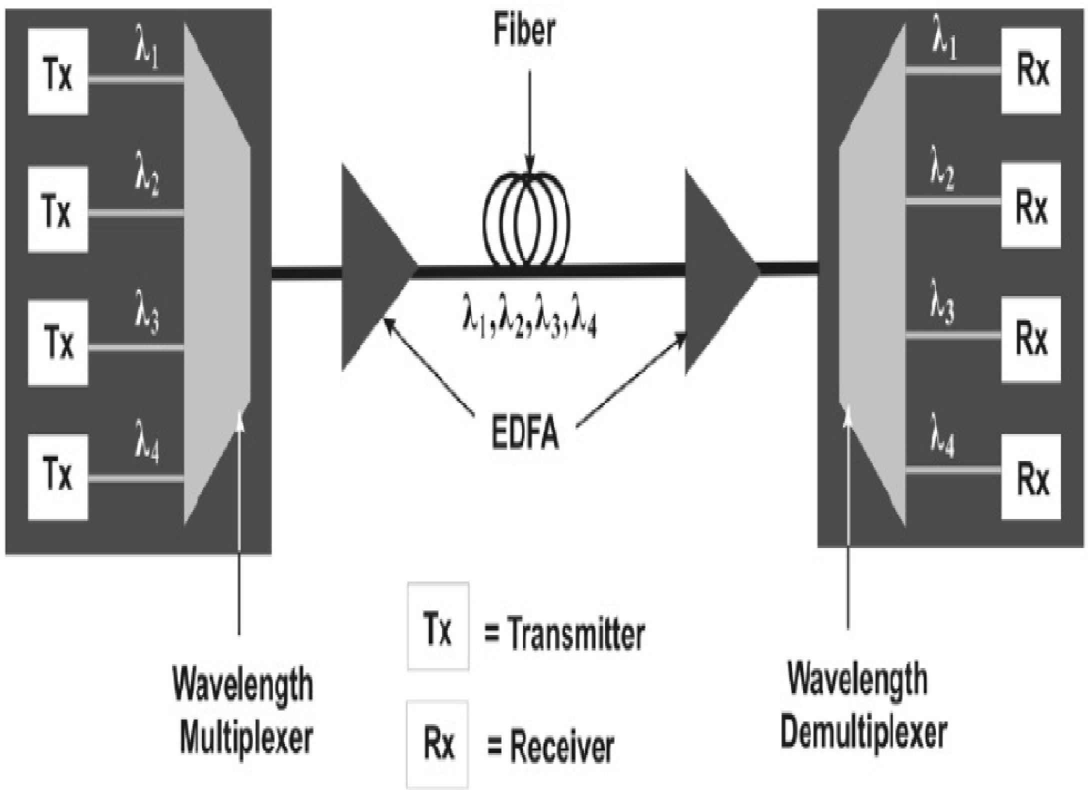


Figure 1.3 Representation of wavelength division multiplexing system [6]

1.2.4 Time Division Multiple Access

In this multiple access, diverse time delays are given to the numerous channels such that each channel gets detected at specified output port of the user. Entire information can be accessed by the end user but for the specific time according to the delays provided to it. As mentioned before that each user gets the different time delays, available bandwidth of the medium can be accessed at different time frames. Frequency of all the channels remains the same and only time varies among them. Times gaps are pre scheduled and these specifies the gap among channels. Channels interference is least in this method however in cellular communication call drops occur if no time slot is there [7].

This technology was first used for telegraphy systems to send multiple signals over a single transmission medium in 1870s. Further 24 channels system was developed in the commercial operation for transmitting an audio signal in late 1953. It was designed for the digital communication however can work in the analog also. There was a standard termed as plesiochronous which was used in the former days and standard digital hierarchy replaced it later.

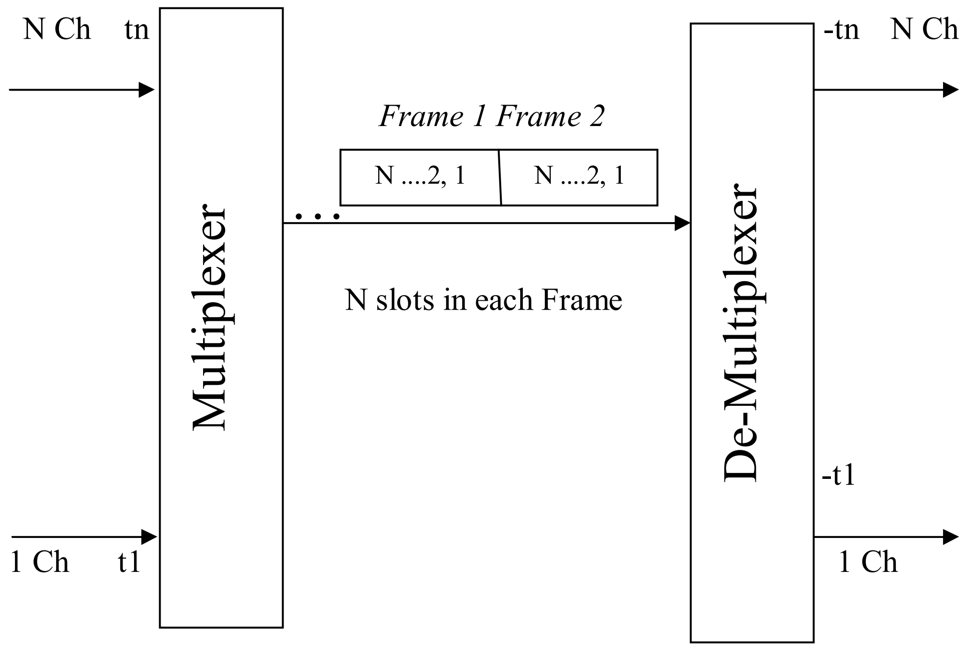


Figure 1.4 Representation of Time division multiplexing system

1.2.5 Code Division Multiple Access

In this CDM access, diverse signature codes are given to the diverse channels such that each channel gets unique code and detected at specified output port of the user by matching the signature code by narrow band filters of fiber gratings. Entire information can be accessed by the end user for the entire time without any restrictions of time and wavelengths. As mentioned before that each user gets the unique code, available bandwidth of the medium can be accessed at same time due to this spread spectrum technique. Frequency of all the channels may vary according to the respective code construction algorithms. This comes in two variants such as frequency hopping and direct spread spectrum technique. Moreover for one dimensional codes, only wavelengths are varied, for two dimensional codes the time is varied with the wavelengths. For 3 dimensional codes, time, wavelength and third dimension of space or polarization is also changed. Codes differences are fixed at the transmitter or are pre scheduled and these specify the gap among channels having different codes.

Code division has been long known and firstly the work was reported in the soviet union in the context of this method. They have represented the three different techniques to separate the signal such as by varying frequency, time and also compensatory. In 1957, military used it in Russia. In 1970, again in Moscow, Altai services were used for code division.

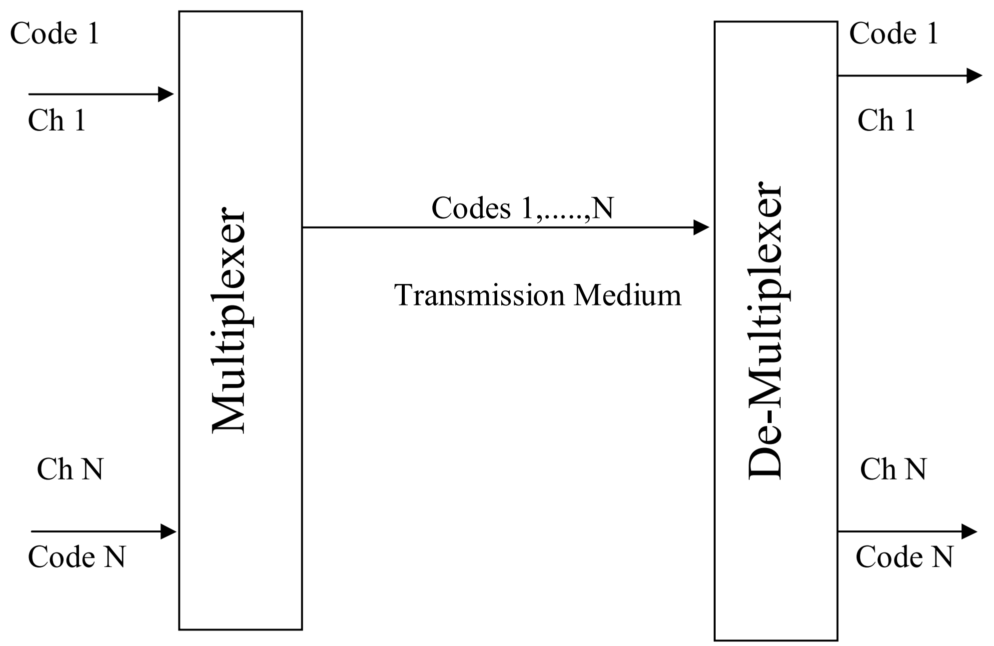


Figure 1.5 Representation of Code division multiplexing system

1.3 PASSIVE OPTICAL NETWORKS

It is acknowledged across the world that fiber optics communicate between starting and end points by intensity signals. Also, this information travels inside fiber optic and there is a requirement to distinguish the signals for sending them to appropriate receiver. In order to send data with low cost, there are simply two important types of network recognized (a) networks that needs external power (2) which does not need external power. Former is termed as active network and later is termed as passive network.

Passive optical network is a promising technology to serve the ever increasing high speed requirement and to fulfil the needs of applications which are bandwidth hungry. It is fiber access network in which splitters are used with the elimination of external power and serve the multiple users or premises. By reducing the required components, the networks lowers the system's cost in the central office as well as at end units as compared to the link where link to single link communication takes place. Architecture of these networks is such that it has three main parts (1) optical line terminal, which is located or present in the central office (2) optical distribution network, consists of optical fiber, feeder fiber etc (3) optical network unit, located at the end point and consists of receivers of users. Major benefit that it eliminate the needs of outdoor active components. Total task of transmission and signal reception is accomplished at OLT and ONU. These networks are high speed and have potential to support large number of channels, and are cost effective. But, if link length reach is compared with the active networks, then PON systems have shorter reach but this is overcome by the benefits mentioned above [8].

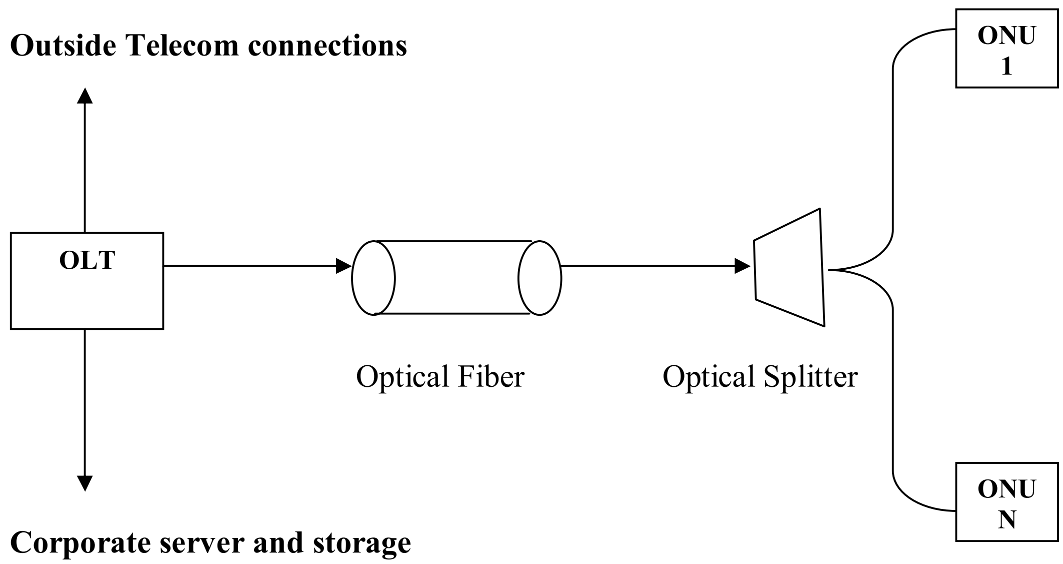


Figure 1.6 Representation of Passive optical networks

1.3.1 Optical Line Terminal

OLT is an important and inevitable part of the PON systems that act as the backbone of the optical fiber network. Major task of the OLT for which this is incorporated in the network is to send a data from central office to client. It transmits information to the network units which is located in the client's location. It starts and manages the ranging process, as well as keeps the ranging information. This equipment in the CO provides the bandwidth to the end equipment and also controls the transmission initiation time. Moreover it also controls the window size of transmission of the end component i.e. ONU transmission data [11].

1.3.2 Optical Distribution Units

Optical Distribution Network (ODN) is an essential path for transmission of Passive Optical Network (PON) systems and openly affects the performance, flexibility, and quantifiability of a PON system. Between OLT and ONU, an essential element of the PON system which present as the physical link for communication is termed as ODN. Its link length accomplishment is of several kilometres more than 20 km. Components that are present in the ODN are passive optical splitters, optical fibers, auxiliary components, fiber optic connector's work together with each other. Start of the feeder fiber is from the cental office or more specifically from optical distribution frame (ODF) and ends at the ODN point for large distance reach.

1.3.3 Optical Network Units

Designs and styles of configuration of ONUs changes reckoning on client's requirements and necessities. The dimensions of it can vary from easy, compact box, being hooked up outside the house to big unit mounted within the big building or flat. ONU can accomplish diverse operations for enhancement of performance of the system. It also can send, accumulate and brush up differing kinds of information returning from client and transmit it to in uplink. Grooming is the method of enhancing and reorganises the information stream thus it might be delivered additional cost effectiveness. On the whole it works as a user interface. This provides interface to particular single user or diverse clients.

1.4 FIBER ACCESS NETWORKS

Access networks often called as last mile networks and these are the links between central office and user which is at end location of the transmission. In recent times, these networks are first and foremost segment of wide networks. Networks, for the most part are costly due to there are distant extra end users as compared to backbone nodes. Some of conventional systems are 1) connection of each household with twisted pair cable 2) housing coaxial cable drops from CATV service providers. Another technology which reliant the radio waves connection is Wi-Max for the last mile. Conventionally, fiber optic have been extensively incorporated in backbone networks for the reason that of their enormous accessible bandwidth as well as very small loss. It is noted that from last decade, networks reliant on fiber optic have emerged as promising technique in metro and core network segments. With the explosive increase in the voice and data and internet put pressure on the medium of transmission and to cope with this, capacity enhancement technique multi-channels multiplexing comes out to be most attractive candidate. On contrary, fiber optic access networks are distant at back and just start to go through a market for the most part dominated by copper cables. LANs incorporating promising optical technology can endow with a rapid access network system that is economical, uncomplicated, scalable, and competent of exhibiting signals to end or last user. Fiber to the x are the systems where x can be any premises, house etc are cost effective networks. These are connected from central unit to user end.

1.4.1 Fiber To The Curb

This network is between central office and curbs near houses or buildings incorporating the fiber as a transmission channel. It is architecture as an alternative for conventional telephone services. However, other medium such as co-axial cables does not have potential to carry signal at prolonged distances. FTTC employ infrastructure of twisted pair cables for providing last mile service. Existing cables which are used in the system makes the system cost effective. Employed wires can cater the high speed for the small link distances. These communication channels have high losses due to which they degrade after travelling few hundred feet. Reach of these systems is thus short.

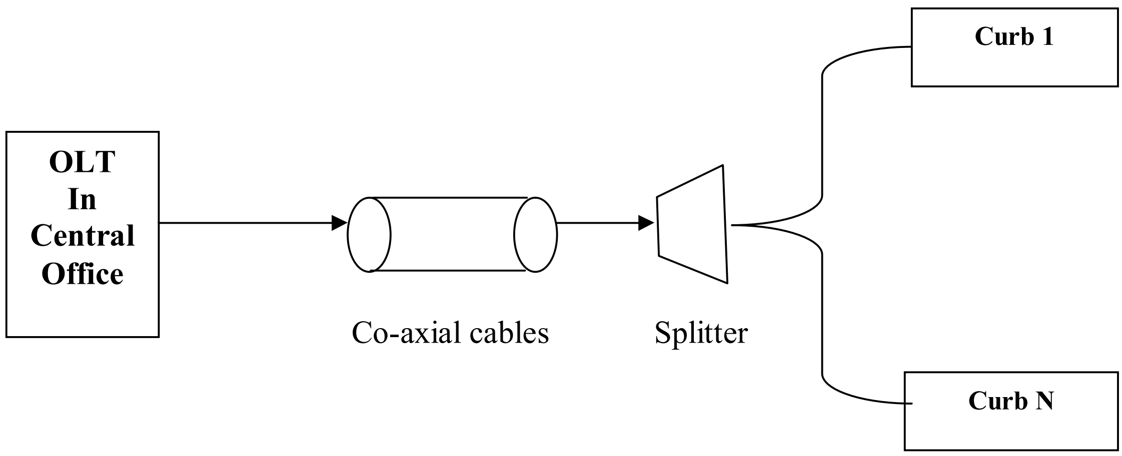


Figure 1.7 Representation of Fiber to the curb

1.4.2 Fiber To The Home

This is the network which deals with the release of a signal through fiber optic from the service provider's switching equipment to a home, by this means changing the existing electrical copper communications like in coaxial cable for telephone wires. Fiber-to-the-home is a fairly recent as well as fast-growing process of offering immensely higher bandwidth to users, and in this manner enabling extra robust internet services and voice or audio and video.

With the connection of houses and any endpoints, together with cellular towers straight to optical fiber enables massive enhancements in what wide bandwidth devices are competent of delivering. This technology gives two types of communications such as uploading and downloading with the speed of gigabit per second. These are future proof technology as conventional technologies extend the confinement of their performance or rapid network, constant enhancements in optical fiber.

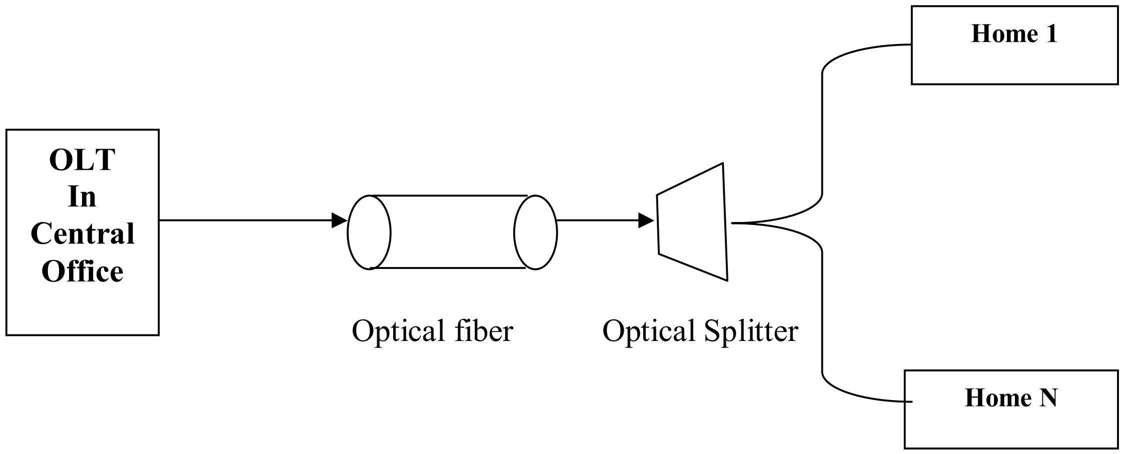


Figure 1.8 Representation of Fiber to the home

1.5 PON TECHNOLOGIES

PON standards are given below:

1.5.1 APON (ATM PON)

Modern industrial progress and economies of range have outlay rising attention to ODNs with Asynchronous transfer module reliant PON. A general depiction of ATM–PON architecture is illustrated in Figure 1.9. Fiber optic is economical and easy to maintain than conventional systems, carriers profited by being competent to lessen expenses as well as in this manner augment profit margins or merely lower prices to client to ward off reasonable threats. Single strands are employed through which transmission takes place and in this way it saves the fiber. It can cater 64 users and again this makes system economical. An additional benefit of the ATM–PON system is the accumulation and deliberation of ATM cells in the optical line terminal. It is perceived that this technology can accomplish savings of 40 percent. For the reason that the ONTs allocate the fiber and wavelength is shared from channels [12].

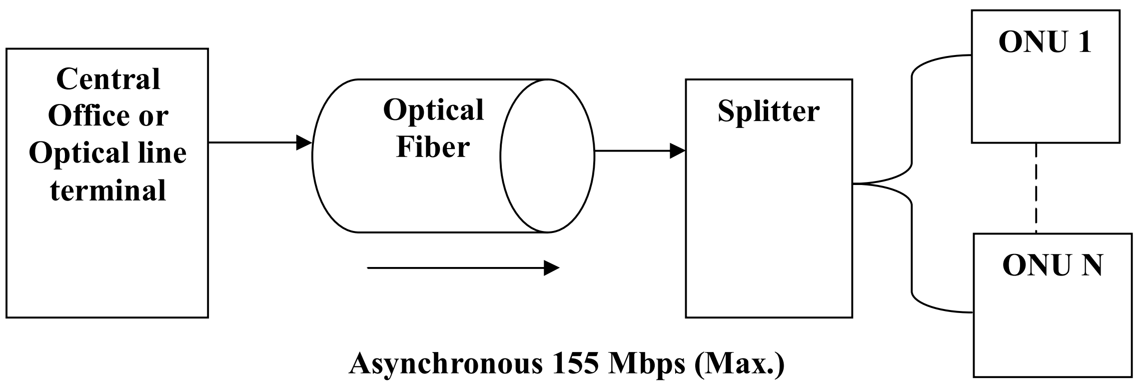


Figure 1.9 Block diagram of ATM PON

1.5.2 BPON (BROADBAND PON)

First standard of PON, which is given by international telecommunication union (ITU) in 1999 year was BPON. Series of this standard is reliant on G.983 and provide working and details of the standard. In the former days, networks which use this standard were also called as APON. This standard was approved by diverse module sellers and system suppliers that collaborated in the Full service access networks. Basically, the actuality is that data using ATM protocol is suggested by the FSAN. Broadband PON standard is a promising method and one of the precedent generation types of optical networks which has the potential to sustain data pace, rapid voice signals, and high speed video services at receiver of client or end user. There are diverse standards also which accomplish the same task but it is noteworthy that BPON has edge over them due to its economical operations. It provides affordable services to the user and keeps the cost lower from central office to the end. There are several methods which are operational to augment the FTTP networks employing BPON. Figure 1.10 illustrates the BPON system [10].

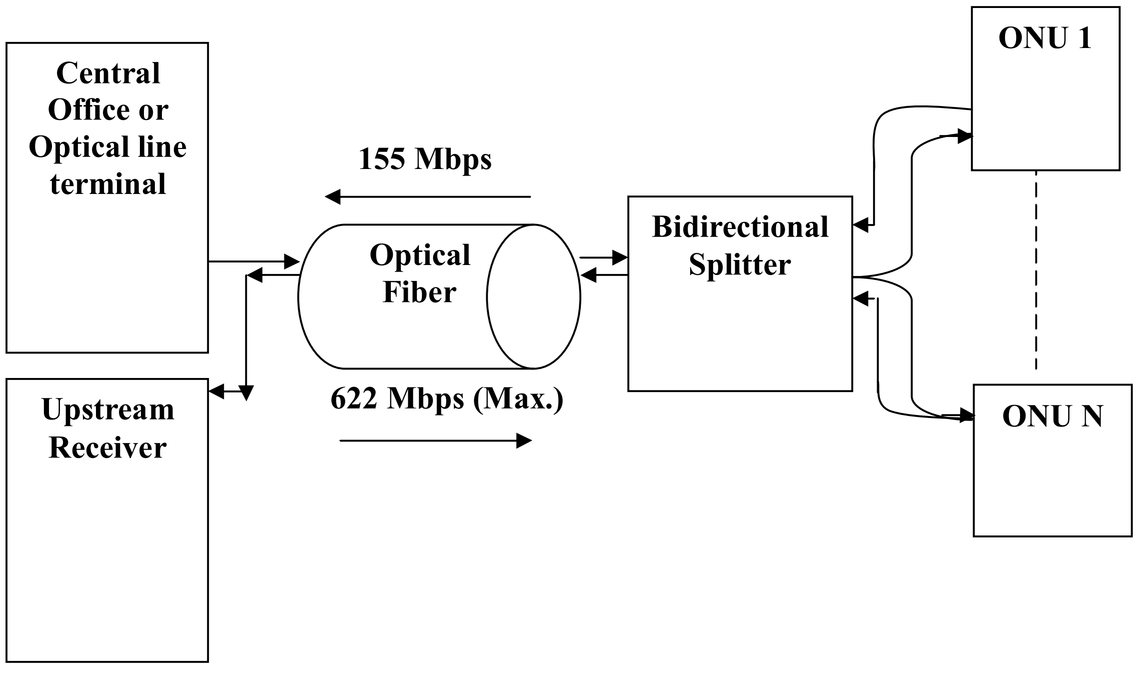


Figure 1.10 Representation of bidirectional passive optical network

1.5.3 EPON (ETHERNET PON)

This EPON deals with the transmission of the frames over the optical network and working is similar to the aforementioned networks in which sharing all the way through the network is simply the specific station in the Ethernet that can recover the data transmitted.

IEEE performed the major role to standardize this PON technology and this group is 802.3ah. Ethernet in first mile is a prime objective and internet in the local loop. The purpose was to substitute the ATM transmission systems because these are too high-priced to realize a point to multipoint communication [12]. Total 64 users can be catered with the EPON and frames can be sent from central office to all end users. Encapsulated frames in EPON are transmitted with the head connection of this to the internet service provider (ISP) [10]. Figure 1.11 depicts architecture of EPON.

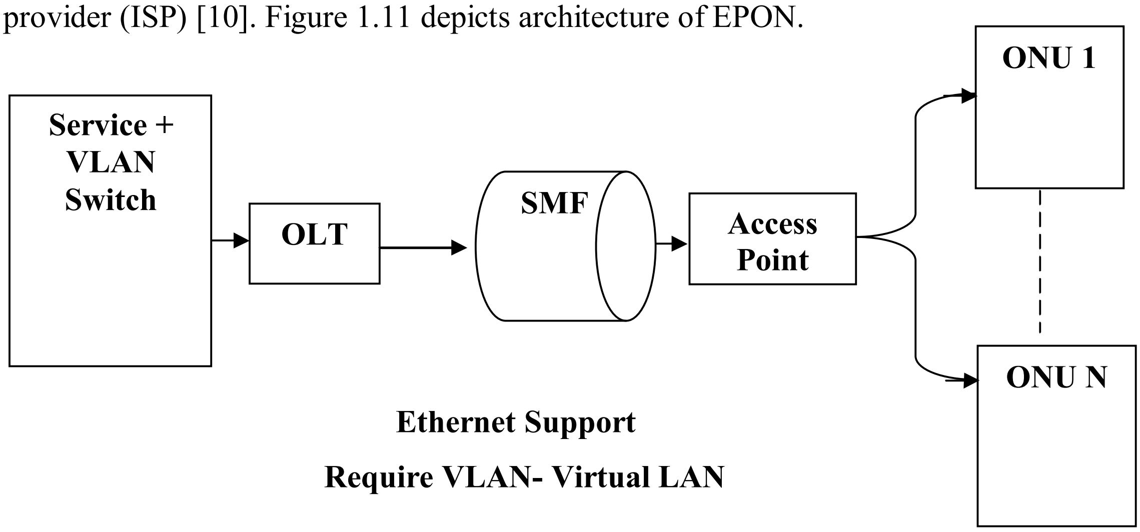


Figure 1.11 Representation of EPON

1.5.4 GPON (GIGABIT PON)

PON technology was existing in the former times such as in centre of 90s. From the time, when the enormous progress of systems has been continuing, diverse standards are recognized and developed. Evolution of the PON networks was from the APON which was the first standard and later on this developed into Broadband PON (BPON). Aforementioned both the standards are well compatible to one another. Afterwards, emerged EPON and Gigabit PON, which offered the immense enhancement in information communication along with prolonged distances as well as enormous bandwidth are noteworthy. In order to deliver the data from OLT to ONU, fiber optic is used as the transmission channel for the rapid communications. GPON's are at present are most important structure of PONs. It can serve up to a 1:64 users ratio by utilizing single strand of fiber. This standard has 95% more efficiency than the conventional copper cables based networks. Moreover, besides efficiency, gigabyte PON provides a cost effective solutions to accumulation of numerous users from beginning to end by employing splitters. It can work in dual direction and has bit rate of 2.488 Gbps in the central office to ONU transmission i.e. downlink and 1-24 Gbps in the uplink i.e. from

ONU to CO. ITU-T G.983 is a standard and it can attain 20 km distance with maximum user 64 in number [10]. Figure 1.12 depicts the GPON system.

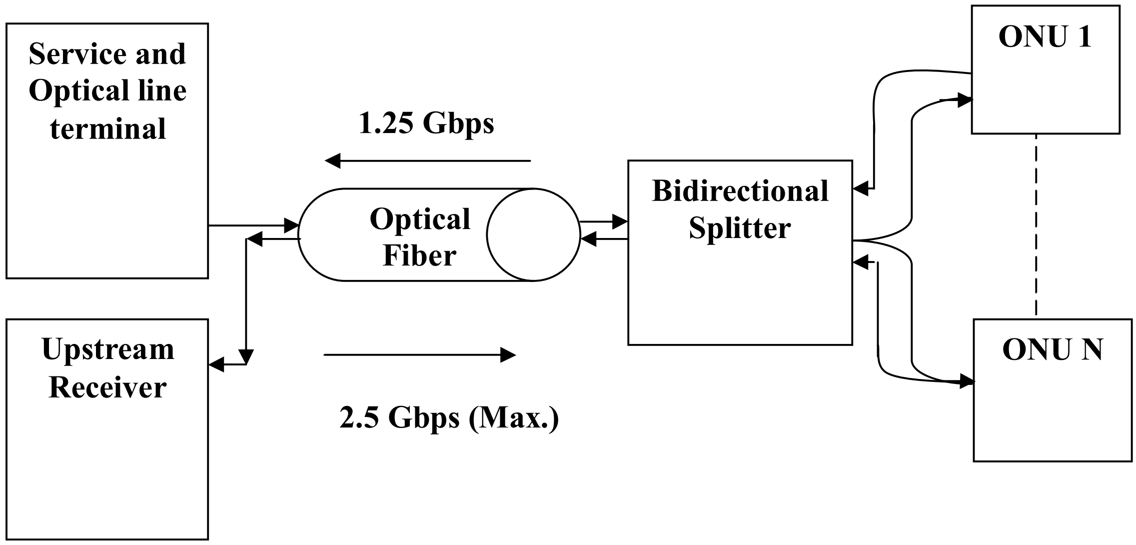


Figure 1.12 Block diagram of Gigabit passive optical network

1.5.5 XGPON

This standard is also famous for the name 10G PON and it has potential of serving application reliant on internet at speed of 10G. It gets standardized in year of 2010 and this is a next up gradation in the GPON and recognized by ITU. Also replaces the conventional wires that connect phone exchange to client's end. FFTX network supports diverse users with optical fiber between the end components. There are mainly three diverse standards such as Asymmetric 10G PON (also called as XGPON1), Symmetric 10G PON (also called XGPON2) and XGSPON. Bit rate of XGPON1 is 10G in the direction of end user from the phone exchange or central OLT and in reverse direction, it is 2.5G. Difference in aforementioned standard and symmetric standard is only that it has same bit rate both directions i.e. 10G on both sides. However, XGPON2 runs on the high cost OLTs and lasers. XGSPON was standardized in 2016 and registered under G.9807.1 ITU-T [12].

ITU-T recommendations:

G.987- Definition, Acronyms

G.987.1- General Requirements of XGPON

G.987.2- Physical media dependent specifications

G.987.3- Transmission convergence specifications

G.988- ONU management

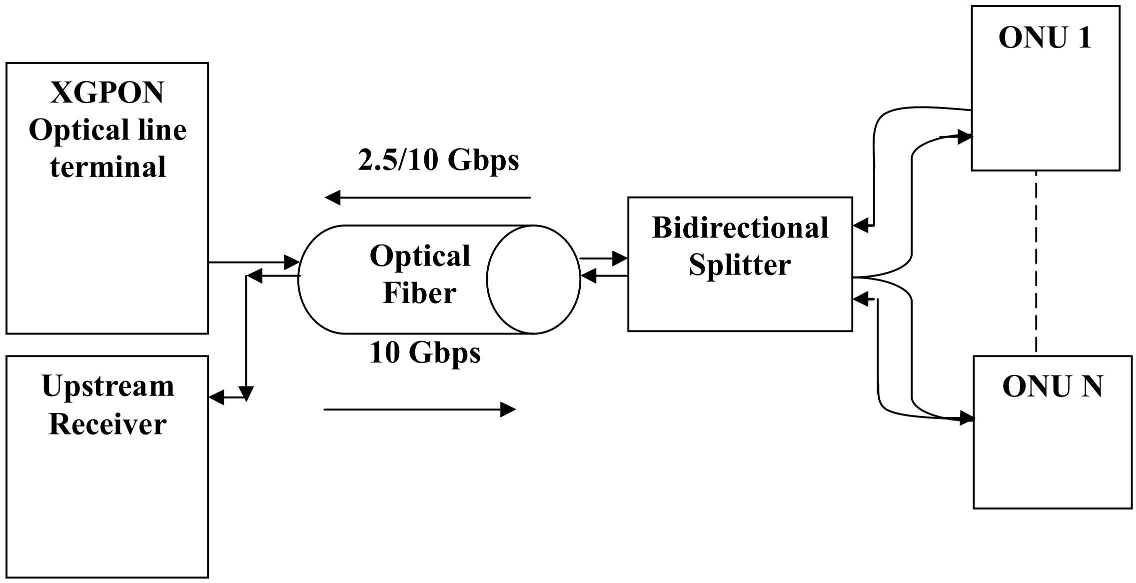


Figure 1.13 Representation XG-PON system

1.5.6 TDM PON

In this standard, diverse time slots are given to each transmitter's channel and accessed by synchronizing there time latencies. TDM-PONs are very famous transmission medium for last mile architectures these days because of less interferences between channels or it may approaches to almost zero due to time difference. It is a base for three different standards such as EPON, TDM-PON and broadband PON. Major Difference of this standard from other available standards is the data rate delivery. The BPON gives less information transfer rate i.e. 622Mb in the direction of CO to end user and 155 Mb/s in uplink which is reverse of downlink. Also other standard EPON serve the system at 1Gbits/second. In the gigabit PON, bit rate is more than last two standards and provides 2.5G in the direction of CO to end user and 1.25G in uplink which is reverse of downlink. TDM-PON provides reliable transmission and less interference among channels. Representation of TDM-PON is shown in Figure 1.14.

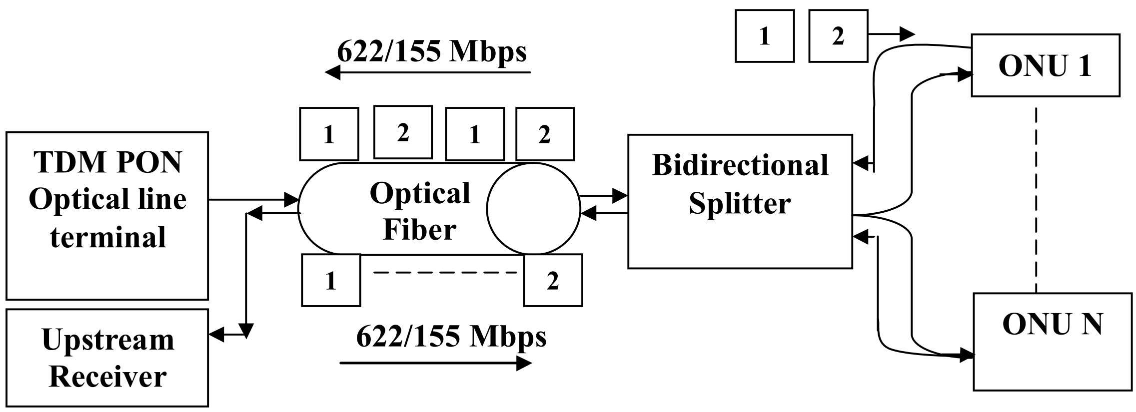


Figure 1.14 Network architecture of TDM PON.

1.5.7 WDM PON

WDM-PON is a pioneering access network standard that has the immense capability to drastically adjust carrier infrastructures. Physical transmission medium and its enormous bandwidth are utilized in the standard by providing diverse wavelengths. It brings different bit rate services receptors at single place such as it can cater residential buildings, official buildings etc and it is a future generation technology which is simple and provide unified access. Potential to cover prolonged distances, security, and use of least external active sites makes it a attentive standard for researchers. Wavelength multiplexing and separation is a basic fundamental of the standard. Individual channels and separation is beneficial and system becomes transparent in providing wavelengths to users. Standard for WDM-PON is not agreed but from some of its explanations, it provides diverse wavelengths for each ONU and best option for pay as you grow systems.

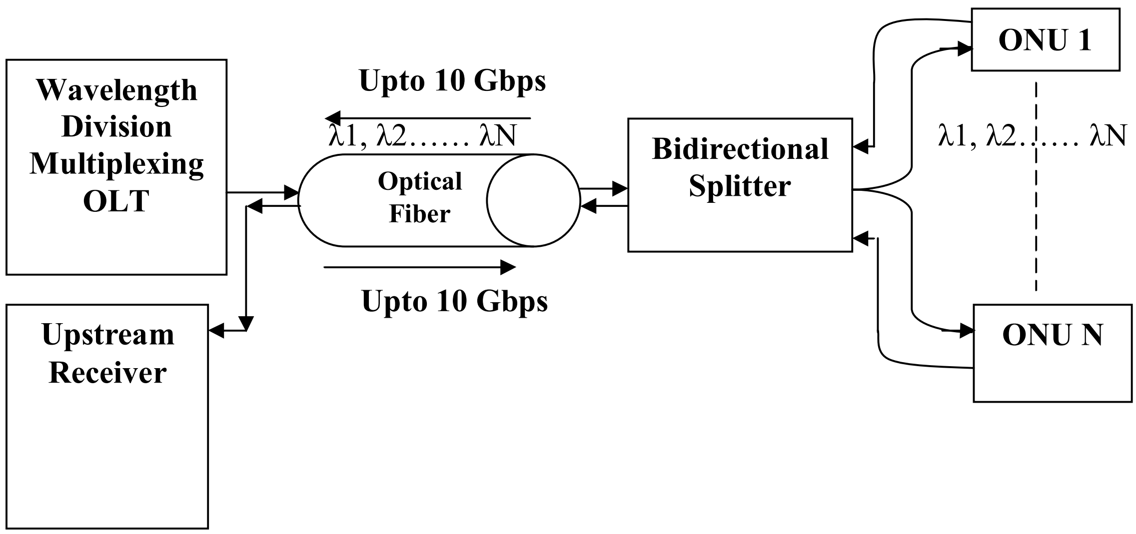


Figure 1.15 Network architecture of WDM PON.

1.5.8 Hybrid WDM TDM PON

Upgradation of present congested networks is essential for the bandwidth hungry application and high speed networks are considered as an ultimate way out to fulfil the requirements. On the other hand, the major problem of high cost of deployment and management of conventional P2P architectures needs a solution. In order to provide a wayout, TDM PON in deployed due to these are cost efficient, reasonable, and less interference prone. However, it has major issue of limited use of bandwidth. Urgent need of the upgradation of TDM to hybrid system which consists of WDM also is to provide high speed and high capacity.

In WDM, because diverse wavelengths are used and system becomes high cost. The hybrid WDM/TDM PON is illustrated in Figure 1.16. Therefore, hybrid WDM/TDM systems serve high data rate and large distances.

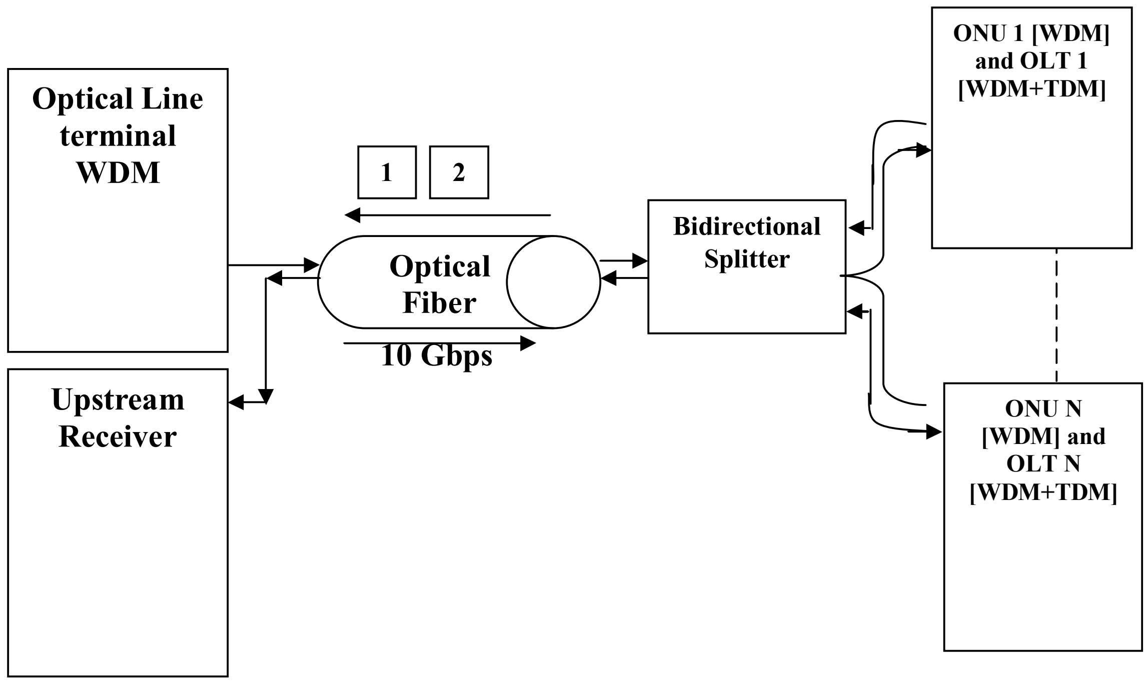


Figure 1.16 Network architecture of hybrid WDM TDM PON.

1.6 MODE DIVISION MULTIPLEXING

MDM is method of joining diverse intensity profile of polarized modes which are different in terms of azimuthal and radial numbers. Since fiber optic has different constrains in the manufactured fiber such as variation in the manufactured diameter of fiber, bending issues, deviation of refractive index. All of these problems are performance limiting of TDM, WDM and does the same task in all the transmissions. However, in mode division multiplexing, due to these defects mode coupling occurs. Mode coupling is basically a transfer of high power of one mode to other. Estimation of this coupling is not simple and in conventional multimode fibers, this coupling at high scale. But, due to recent developments in this area, brings down this coupling to lower level. The effective length of fiber at which mode coupling initiate and stops is called as Length of coupling. In developed fiber, it may be of several kilometres and thus are able to cover prolonged distances. Mode coupling is purely not a problem; however it has some constructive effects also such as it enhances the bandwidth of modulation, less pulse broadening due to difference of propagation mode's group delays. Power which is shared with radiating modes has adverse effects on the system. A lightwave is a form of electromagnetic wave travelling over the void of exterior space. Energetic electric charges create waves of light in the form of waves that are transverse in nature which have magnetic and electric constituent. In, EM wave, when they travel, the vibrations occurs in different plains. The vibrations occur in a single plane in polarized light waves. Un-polarized light is converted into polarized light which is referred to as polarization. When different intensity profiles are fed into fiber, these are termed as mode mode division multiplexing. Considering electromagnetic nature, different categories of modes (transverse and hybrid) depending upon the angle between electric field vector and axis of transmission medium are there. In other words, the natural modes can entirely be transverse (TE and TM) or have longitudinal elements. Grouping together all different modes into a single series is known as Linearly Polarized (LP) modes. These LP modes can be obtained, from (a) By changing refractive index of core (b) By changing core size (c) By changing the wavelength of wave (d) By setting a specific Eigen value [13] [14].

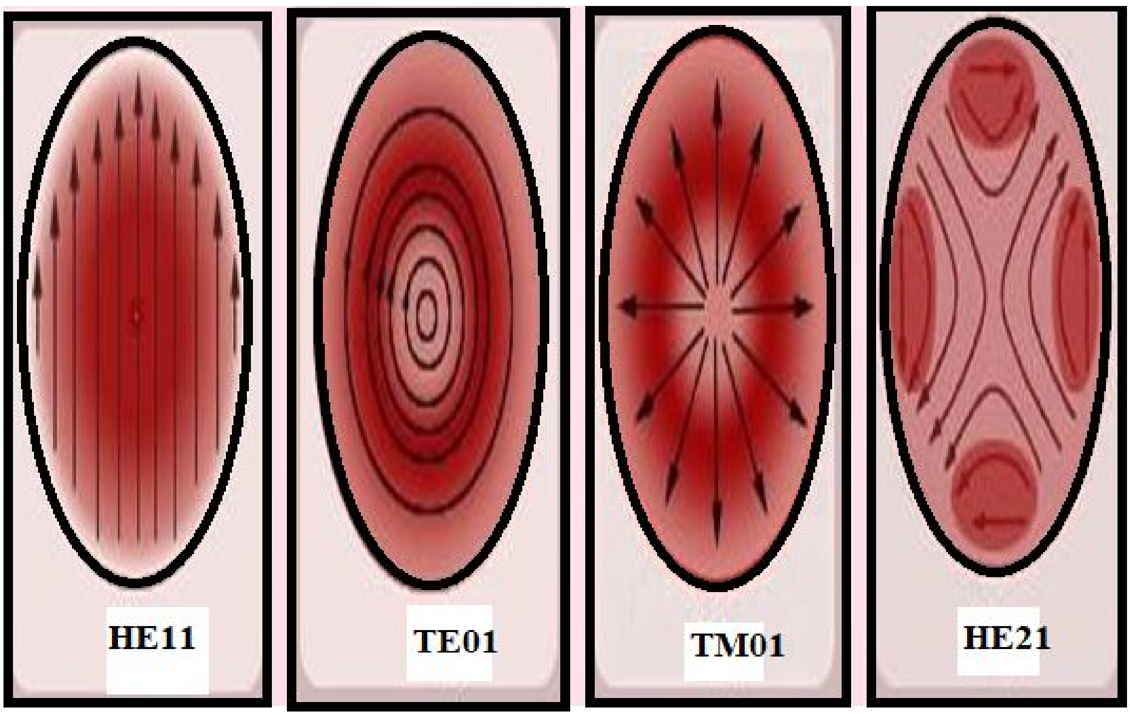


Figure 1.17 Few Electromagnetic modes in optical domain

Few Electromagnetic modes of light are depicted in Figure 1.17. It is perceived from figure that,

- HE_{11} modes are having only electric field acting in the upward direction when amplitude is highest at the axis point and it tends to decrease with outward radial movement. The HE_{11} mode is the lowest order mode.

- The TE_{01} and TM_{01} modes have circularly symmetric electric fields. In this, amplitude is highest at the center point and it tends to decrease with outward radial movement.

1.7 NOMENCLATURE AND INDICES OF EM MODES

For the understanding of nomenclature of mentioned EM modes, field patters are important to comprehend. Azimuthal plane and its fluctuation according to the phase Φ is denoted "v". We have taken a pair (v, m) for the consideration and study of indices. These are also understand as no. of cycle variation in a plane. On contrary, number of maxima, zero crossing and minima in azimuthal plane is dictates by "m". If zero crossing are calculated, index "m" always one more than these zero crossings. Figure 1.17 depicts that the HE11 mode which is hybrid in nature has one cycle for Er and Eϕ in azimuthal plane and there is no zero crossings in the plane therefore their nature is decreasing.

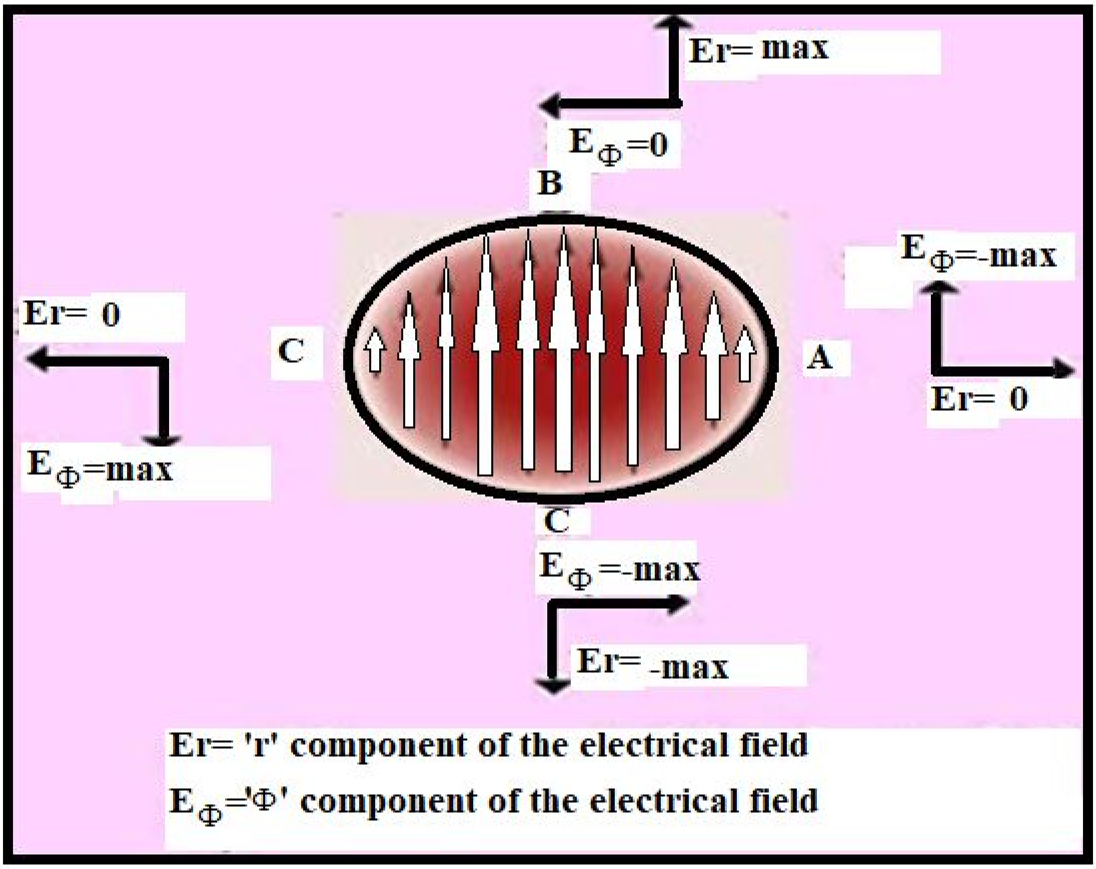


Figure 1.18 Variation of the field components

This can be seen from Figure 1.18. Alike outcomes can be prepared for the modes TE_{01}, TM_{01} and HE_{21}, and the field direction of variation can be estimated from the acquaintance of the 2 indices of mode. Fields are symmetrical in the circular direction about axis of the medium of communication and azimuth plane have no zero crossings. Depiction of field patterns is illustrated in Figure 1.18.

1.8 LINEARLY POLARIZED (LP) MODES

It is clear from above discussion that the electromagnetic fields are almost transverse in nature and also polarization of them is linear. Direction changes the field paterans and they never are identical [15]. Means of aforementioned statement is the all fields provide same or identical polarization and are showing same linearity. Intensity variation are identical and patterns are too. Figure 1.9 depicts the orientation of the polarization which can be horizontal or vertical.

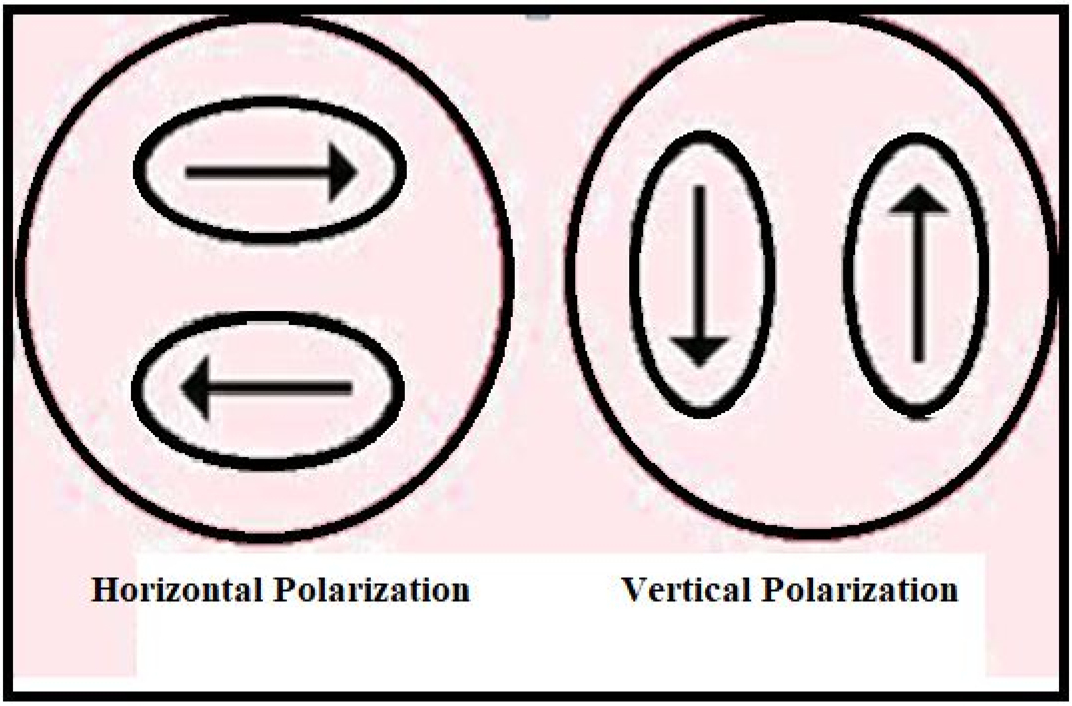


Figure 1.19 Polarizations of the linearly polarized modes

Mode number can be calculated as from the equation (1):

$$Mn = n + 2m - 1 \tag{1}$$

Where Mn is mode number, n is azimuthal no. and m is radial number.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a detailed literature survey of passive optical networks has been done. The essential parameters used to agree on the performance of PONs are bit rate (BER), Q factor, optical signal to power ratio (OSNR). Many authors have worked in this area. The work done by various authors on various PONs architectures and topologies has been summarized in the literature.

2.1 LITERATURE SURVEY

Anis M. I. *et al.* [16] demonstrated a system with TDM/WDM PON and a work was accomplished to integrate two diverse standards in one system. Back compatibility in optical networks was demonstrated by author. TWDM PON system was integrated with Gigabit PON and also triple play signals were supported. Cost efficient system and reliable system was given as required in next generation NGPON2. Data, audio and video were sent over GPON and diverse pulse shapes, modulations were analyzed. Proposed system was a new approach for the pay as you grow services. This was an up-and-coming promising to cope up with future requirements of bandwidth and permits service giver with a way out to expand system. Q factor along with BER was evaluated in the system for diverse modulations and pulse shapes. It was perceived that NRZ for TWDM PON and RZ-DQPSK in case of GPON were optimal.

Xia C. *et al.* [17] proposed a first of its kind passive optical network with the incorporation of Gigabit PON and also with mode division multiplexing. MDM was used for the suppression of uplink interferences. System was successfully attained a distance of 20 km with no errors and the transmission of 3 modes in GPON system which can be used commercially were demonstrated. Mode group delays were also checked for 10 diverse modes.

Goyal R. *et al.* [18] designed a 256 ONU bidirectional hybrid wavelength/time division passive optical network by using 10 Gbps data rate at 190 KM distance for upstream and downstream links. Both transmission links works at only single carrier path, to make a system cost effective. To reduce the interference, system works at individual wavelengths for both upstream and downstream. It also eliminates the Rayleigh scattering (RS) and Stimulated Brilliuon scattering (SBS) by using phase modulator. CCONU technique was used at receiving end with less no. of lasers. to decrease the cost of the system. These advantages provide the acceptable range of Q-factor and bit error rate.

Singh S. ***et al.*** **[19]** designed a novel 120 Gbps WDM-OTDM hybrid optical 120 multicast system. To provide a unicast and multicast data transmission system different modulation schemes were used such as polarization, sub carrier modulation and differential PSK modulation. Polarisation and sub carrier modulation were used to provide unicast data transmission as well as to expand the capacity of the system by reducing several dispersion effects. On the other hand DPSK works at 40 Gbps to provide multicast data communication. To evaluate the performance of the system, different launched power levels were examined at various distances and extinction ratios of the received signal. Performance of system was analysed by studying the different values of parameters such as Q-factor and BER.

Kaur A. ***et al.*** **[20]** demonstrated 4 channels OFDM time/wavelength division based passive optical network for optical line terminal. At Upstream transmission was achieved by wavelength reusing and NRZ line coding based 4 channels, 10 Gbps bit rate. Results were evaluated from the constellations and eye diagrams. System achieved the acceptable Q-Factor 6.76 for downstream as well as upstream up to 60 km. Total Power budget was calculated as 24.56dBm.System provides no. of advantages with large bandwidth and high capacity.

Houtsma V. ***et al.*** **[21]** discussed various ways to diminish the expenditure of the system to achieve a high data rate in passive optical networks. TDM PON Duobinary modulation format was introduced to provide these key advantages. Several pulse shapes were examined to find best modulation scheme. They compared different modulation in PONs based on its advantages and disadvantages. It provides a high speed network by using 25 Gbps and 40 Gbps. different speeds.

Abbas H. S. ***et al.*** **[22]** proposed different approaches based on different hybrid techniques to improve the performance of next generation PON. They investigated next generation PON such as EPON and GPON with respect to its physical layer requirement. They also compared various technique with respect to its advantages and disadvantages.

Liu X. *et al.* [23] reviewed the history of passive optical network. To acquire high speed network, large no. of channels author described fifth generation wireless technologies incorporating different modulation schemes, detection techniques and digital signal processing to make the system cost effective. They also explained the collaboration of radio access RAN and PON to provide the high traffic network. This is a key advantage of fifth generation PON, which improves the performance of the system.

Andrade M. D. *et al.* [24] described various integrated time/wavelengths division PON systems with coherent-detection to represent a novel optimization architecture reliant on Mixed Integer Linear Programming (MILP) to achieve advantages like lower cost, large bandwidth utilization, and excellent power budget. To ensure the overall performance of System various loads and length were compared.

Bindhaiq S. *et al.* [25] demonstrated a next generation PONs to improve the performance of the system by providing accessible bandwidth and better cost efficiency, without any changes in ODN. Second generation (NG-PON2) passive optical network incorporating Time/wavelength division was best network to fulfil these requirements by using tunable transmitter and receiver. They investigated the data rate with sufficient budgeting of power for both OLT to end user and vice versa.

Shaddad R. Q. *et al.* [26] demonstrated a 2.5Gbps FiWi (fiber-wireless) access network using frequency division /time division PON with 24 Km link distances. They also investigated the performance of the physical layer based upon large no.of access points (APs) and it's supporting ability in optical domain. In the system, a link of 24 Km supplementary attached with 50 m non-wired link at bit rate of 54 Mb/s or can 30 Mb/s by incorporating wireless fidelity.

Emsia A. *et al.* [27] proposed a DQPSK hybrid TDM/WDM networks for improving the capacity of the system. Proposed networks provide a large bandwidth with cost effective transmission by using 40Gbps upstream and 120Gbps downstream data rates. The access budget of 33.4 dB was investigated for every WDM channel at 10Gbps when DPSK was used with wavelength splitting ratio of 1:512. But 40 dB power budgets were obtained in case of DQPSK with as per wavelength splitting ratio of 1024.To get better performance of the system, proposed method also reduce the nonlinear effects.

Pandey G.*et al.* [28] designed a 16 channels colorless wavelength division passive network by using 10Gbps in both downstream and upstream. OOK and XGM data modulations were used for downstream and upstream links respectively. To make the system cost effective. Various no. of optical device were employed such as modulator typically EAM, RSOA, coupler, Wavelengths conversion were done at upstream link to operate the all network unit in colorless mode. They evaluates the effects of extinction ratio of delay interferometer (DI) on output optical CSR.

Bi M. *et al.* [29] demonstrated novel WDM-OFDM-PON system with 10 Gbps upto 100 Km coverage without the requirement of any receiver. For downstream transmission OFDM signals were sent at 10Gbps per wavelength. On the other hand on–off keying (OOK) signals were sent over upstream link. Optical filter with electronic controlled liquid stage used for at the same time selection of downlink as well as uplink signal chirp. Results were evaluated at 35.6dB power budget to transmit the signals over 25km fibre length for supporting 1:512 splitting ratio. 34.4dB power budget evaluated for transmission up to 100km link distance.

Jaumard B. *et al.* [30] described the PON architecture for supporting 128 users for saving the cost and to improves the system performane.They described the performance of the system by classifying three different networks units such as splitter or arrayed waveguide, location of the switches and dimensioning of access network. Based upon 128 user support numerical calculations were performed.

Dixit A. *et al.* [31] architected a new design of time/wavelength division (TWDM) PON by incorporating WSS.WSS were used to enhance the performance of the system, by increasing link distance, more flexibility, less cost, high security and 60% energy saving capability at the optical line terminal. It also provides the multicasting gains and switching suppleness.

Chow C. W. *et al.* [32] explained migration techniques from TDM-PON to WDM-PON incorporating different modulation schemes. At downstream transmission link signal were transmitted by DPSK modulation and ASK modulation used for uplink signal. Simultaneously to demodulate the downlink signals and choose appropriate downlink wavelength optical filter was established at base station. Experimental results revealed the performance of modulated wavelengths for upstream transmission which provides a successful transmission up to 64 splits.

Chien *et al.* [33] Fiber laser reliant WDM-PON system is demonstrated in 2011 with secondary trees. There was significant boost in the dynamic assignment of wavelengths and security. The central ring can offer augmented protection for the distribution network and RN system performs the function of dynamic wavelength assignment and provides the enhanced security under the situation that the components are arranged in the unidirectional. It also provides the protection against the fiber cuts. For balancing the load of the system and reduced the power budget, CO system were designed. To drop the wavelength RN used a WB dynamically. To check the feasibility of the system, experimental results were examined at different stages of the networks

Goyal R. *et al.* [34] demonstrated the performance of hybrid time/wavelength division optical network using 128 ONUs over 28 Km link distance in FTTH. System sufficiently provides the transmission of three data signals such as text, video and voice at different wavelengths and sufficient data rates by using NRZ line coding. At 1.25 Gbps bit rate text and voice signal used a 1480-1550 wavelengths band. For video signals used a`1550-1560 wavelengths band to transmit signal at 800 Mbps. These proposed systems provide better results and high capacity system.

Zhang R. *et al.*[35] designed a 40 GHz bidirectional hybrid TDM/WDM PON system for ROF link by incorporating 4 QAM signal at 10 Gbps data rate for both wired and wireless services over 30 Km link distance. For Bidirectional transmission Single mode fiber was used. To decrease the cost of system less no of lasers were used in ONU. Results provide the distortion less transmission at 10 Gbps for 4 QAM up to 30 km coverage.

Novak D. *et al.* [36] reviewed the performance of 60 GHz Radio-over-fiber wireless systems. They described the advantages and disadvantages of ROF systems based upon its usages in different wireless applications. This designed systems used a 60 GHz frequency band based on the shifts of carrier signals due to SBS.ROF wireless systems incorporates the multi wavelength intensity laser sources to eliminate the stimulated scattering (SBS) in the fiber. It also provides a large distance area at high speed communication to compensate the dispersion effects. They elaborated the usages of ROF in 5 G system by describing its various advantages.

Sarup V. *et al.* [37] discussed ROF-PON wireless system incorporating WDM and OFDM multiplexing techniques. To achieve dual bidirectional transmission WDM-PON systems were used for proposed wireless transmission. They investigated a OFDM

ROF-PON systems due to its large no. of advantages such as bandwidth efficiency and less sensitive to fiber dispersions. In order to achieve a large distances using ROF signals, basic and cost effective technique such as filtering with FBG was used to enhance modulation depth.

Elmagzoub M.A. ***et al.*** **[38]** demonstrated full duplex ROF–PON systems to provide a large number of users at lower cost. To achieve a high bit rate and reduce the requirement of more optical fibers various PON standards are discussed in this work. ROF PON systems were classified at several modulation techniques. Downstream signal were transmitted by 16 QAM modulation format at 40 Gbps bit rate. They also used Polarization division at downlink transmission to provide efficient bandwidth, which become almost 2 times with less power penalty (1.5 dB) Time division multiplexing used at uplink transmission to provides a 10 Gbps bit rate over 20 Km link distance.

Cheng G. ***et al.*** **[39]** proposed and analyzed a novel ROF system at 60 Km link length. To implement the performance of the system optical interleaver and external modulator were used to produce dual coupling-frequency millimetre waves for two BSs. The re-modulation scheme was used to generate a sufficient uplink connection. To make a cost effective system they shared a same laser source at central office and it also generate two upstream signals at SMF with 0.5 dB power penalty.

Aldhaibania ***et al.*** **[40]** proposed a 2.5Gbps ROF-GPON system incorporating DPSK modulation. Single PON were used to connects the TDM GPON and WDM GPON systems which reduced the cost and provides the high bit rate. Radio signals were transmitted at 25 km SMF to support 32 and 64 clients. System results were analyzed based on optical signal-to-noise ratio (OSNR), received power, error vector magnitude, constellation diagram and eye diagram. By increasing the link distance at 50 Km, value of EVM also increased to 30.3% But OSNR and received power were decreased to 35dBm and -24dbm respectively at 50 Km distance

Aldaya I. ***et al.*** **[41]** reviewed the performance of various optical components such as narrow spectrum intensity lasers, analog lasers, and wide band modulators that used in the millimetre wave generation in ROF wireless systems. They discussed the advantages of optical components to provide a better performance with less cost. Author also described the different methods to generate a mm wave in ROF system.

Zhu M. *et al.* [42] demonstrated two architecture of radio ROF for next generation broadband contact less wireless network using 60 GHZ and millimetre wave of several GHz. They introduced various network services to enhance the performance of next generation or future generation PONs with cost effective way. A 60 GHz system was used and it integrated with the multi-channel ultra-dense wavelength multiplexing over single mode optical fiber (SMOF). To achieve a high no. of ONUs and large system capacity several heterodyning method were used with dense WDM or ultra-dense WDM ROF system.This demonstrate system was based on 60 GHz ROF with on off keying.They also measured the Effects of cross phase modulation over different link lengths in the system.

Mitatha S. *et al.* [43] demonstrated a high frequency (THz) wired and wireless WDM-ROF networks to enhance the signal security was given by the particular filter of particular wavelength, which run by the centralized unit and channel capacity. They analyzed wavelength enhancement in optical communication. Current system was capable to support multiple links at same instant in the THz range.

Hsueh Y. T. *et al.* [44] designed a 5.65 Gbps hybrid dual directional ROF PON systems incorporating WDM and OFDM.In this system, use of multi wavelength generation as well as the carrier-reuse was done to provide better performance of radio ROF systems. Signals were transmitted over 25 link distance with 16QAM OFDM modulation for both upstream and downstream transmission links. Result revealed that WiMAX 17.28-Mb/s bit rate were used for OFDM-64QAM OLT to ONU downlink and for uplink, 11.52 mbps 16QAM to achieve acceptable range of EVM given by IEEE.

Kim A. *et al.* [45] proposed a 60 GHz broadband radio ROF wireless system with the employment of millimetre waves, to increase the distance of wireless transmission from LAN to MAN. Intermediate frequency feeders was used to achieve 155 Mbps bit rate at 60GHz ROF transmission with $<10^{-6}$ BER by using 2.6 m cell radius. Radio signal were transmitted by Hon antenna. Channel estimation, synchronization was used to get better signal to noise ratio and to get low BER. Results showed the improvement of SNR (6dB) at 10^{-6} BER.

Gill H. S. *et al.* [46] designed a DD WDM -OFDM PON system by incorporating secure hash algorithm (SHA) to achieve high security networks. Logistic chaos map was used to accumulate the orthogonal frequency division multiplexing's symbols in time as well as frequency domain. For transmitting signals over single mode fiber, a message-digest of scrambled and descrambled orthogonal frequency division multiplexing signals was compared at the OLT and ONU, respectively. In OFDM ,32 QAM signals were transmitted over 50 km SMF at 10 Gbps bit rate.

2.2 GAPS IN STUDY

Passive optical networks are getting attention of the researchers because of large number of benefits given by these systems. But, till date, work of the upgradation of conventional PON standards by integrating them with latest high speed standards is reported very less. More specifically, back compatibility and integration of NGPON2 and GPON is an interesting task for upgrading the existing standard to high bit rates for the fulfilment of ever increasing requirements of end users. It provide the benefits of pay as you grow and also this joint operation of NGPON2 and GPON provides the cost effectiveness and saves the strands of fiber by upgrading the conventional already deployed systems. Limited work was reported to integrate back compatible system.

Performance enhancement of PONs is a major and most important work to be accomplished. Performance of the back compatible integrated NGPON2/GPON depends majorly on design of optical line terminal i.e. depends upon multiplexing and modulation used in the work. Mode division multiplexing is future generation extensive important access method which has ability to save the cost, support ultra high bit rates and due to immense development also covers long reach nowadays. But very few papers are reported using MDM in PON.

Investigation of linearly polarized modes is an essential work for the performance enhancement. It is worth to know that higher order modes can act better than lower order modes and vice versa. More specifically, mode profiles have ability to effect the system and needs to be investigated. No work is reported in passive optical networks.

2.3 RESEARCH MOTIVATION

The unpredictable augmentation of the needs of rapid communication and massive bandwidth hunger direct researchers to employ fiber optic in the access networks in place of copper cables. In order to use massive bandwidth of fiber optic cables, a promising and pioneering access technique is passive optical networks which benefit user with large bandwidth. To cater high speed, WDM-PON and TDM-PON network are extensively user. But these systems have their own limitations such as WDM needs equal number of lasers as the channels which increase the expenditure on the system.

Also suffers from wavelength crosstalk and degradation of performance occurs. On the other hand in TDM-PON, interference is negligible but due to time latency and time gap, synchronization is issue at receiver which degrade the performance of the system. Thus the use of mode division in passive optical networks, open up the new path of research in PONs.

2.4 OBJECTIVES

Objectives are formulated by analyzing the problems of security breaching in the reported passive optical networks and listed as follows:

i. To study the backward compatible integrated NGPON2/GPON system.
ii. To propose a mode division multiplexing in backward compatible integrated NGPON2/GPON system.
iii. To investigate the different order linearly polarized modes in back compatible TWDM/GPON.

2.5 THESIS ORGANIZATION

This dissertation is categorized into five different chapters.

In first chapter, basic introduction about optical access networks, multiple access methods, passive optical networks and its standards, mode division multiplexing is discussed. Optical fiber based architectures and electrical cables reliant networks are also elaborated.

In chapter 2, various related works of passive optical networks, mode division multiplexing, different PON standards based architecture which was used in past are given and discussed. Form the literature, various limiting factors in performance enhancement of PONs are identified and problem is formulated. Research motivation is also given which inspires us to work on this technology of integrated PONs. To overcome the issue mentioned in research gaps, objective are also proposed and written in the chapter.

In third chapter, a performance improved integrated back compatible NGPON2/GPON system is investigated by incorporating mode division multiplexing in the system. Triple play services are supported and mode division is used in both architectures and results are evaluated in terms of signal to noise ratio, BER and quality factor. Further different order modes are also analyzed in the system.

In fourth chapter, provides the results of the investigated performance improved integrated back compatible NGPON2/GPON system with mode division multiplexing in the system. Different distances, launched power levels, linearly polarized modes are taken into account for investigation and results are observed by analyzing Q, BER and SNR.

In fifth and last chapter, outcome of entire investigation is given and points of future enhancement in proposed system are also discussed.

CHAPTER 3

PERFORMANCE ENHANCED BACKWARD COMPATIBLE INTEGRATED NGPON2/GPON SYSTEM USING MODE DIVISION MULTIPLEXING

Time and wavelength division based PON is a groundbreaking technology in the field of access networks and an essential driver for NGPON2 (next generation passive optical network). In this work, a backward compatible integrated TWDM PON and Gigabit PON is demonstrated by incorporating mode division multiplexing. Video overlay is also considered in this work along with back compatibility of PON standards. Cost efficient and reliable system is proposed as required in next generation access networks. Data, audio and video are sent over TWDMPON/GPON and diverse linear polarized modes are analyzed. Proposed system is a new approach for the pay as you grow services. This is a promising integration of two diverse standards that can work on same feeder fiber or ODN without any extra deployment of fiber. Q factor along with BER is evaluated in the system for different link lengths, and different intensity profiles i.e. LP mode profiles. It is evident that TWDM PON is better than GPON and odd LP mode provides better performance in both PON standards.

3.1 INTRODUCTION

The explosive growth in the requirements of high bandwidth for bandwidth hungry applications has direct to a sharp augmentation in the competences of fiber optic [47]. Cloud reliant solution and increase in video online services like triple play services reported a drastic increase in internet traffic [48]. As the traffic of internet based services increases, this opens up business opportunities for telecom companies to serve value added services [49]. Gigabit passive optical network is perceived as practical way out to fulfill the high bandwidth requirements with Fiber-To-The-Premises access [49]. It works on guaranteed QOE and low latency with elimination of high bit rate issues by supporting triple services over PON [50]. In addition, reliable services paying attention towards users requirements are also given by Gigabit PON. Internet access, audio and data connections is provisioning service comes under triple play [51]. Service providers have incorporated Gigabit PON for communication by implementing FTTP which becomes an inevitable part for serving bandwidth hungry requirements [52]. Optical line terminal present in central office, optical fiber and distribution network and optical network unit located on user premises are three essential components of GPON [53].

First and foremost asynchronous PON and broadband PON are deployed commercially. ATM PON works on the transmission data speed of 622 Mbps and for enhancement of the standard, a packet based high speed standard is provided i.e. GPON [54] [55]. GPON is simply an alternative of aforementioned PON and BPON which offer 2.488 Gbps speed in downlink and 1.25 Gbps in uplink. Extensive works are reported to improve the performance by changing the wavelengths [56], to reduce the overall cost of the system by increasing bit rate per channel [57]. But, fiber linear and nonlinear limitations degrades the performance of the system at high bit rates and at different bands wavelengths. GPON has system reach of only 60 km and 20 km. For high dara rate and high capacity with long distance transmission, next generation PON systems are prominent. NGPON standards are divided into two stages such as 10 Gbps downlink speed based NGPON1 and 40 Gbps speed based NGPON2 with economical deployment. NGPON2 is getting attention of researchers due to numerous advantages such as reuse of ODN, mobility of wavelengths, backward compatibility, and enormous bandwidth and sharing of infrastructure [58]. TWDM-PON is also considered in the NGPON2 as WDM-PON and OFDM-PON are already considered [59]. TWDM-PON delivers data speed of 40G in downlink and 10G in uplink and also has potential to support back compatibility with already deployed conventional PONs [60]. Coexistence of PON standards, supportability of triple play services, packing of large number of channels into standard, high bit rate to each user are the needs of future PON networks which should be met in near future. Numerous researches are studied and proposed for performance enhancement of the PON systems such as optimal polarization launch [61], dispersion compensation [62], diverse modulation formats [63], and optical amplifiers [64] etc. However, these approaches are somehow increase the performance but also increase cost and complexity of the system.

In this research article, a performance enhanced mode division multiplexing based backward compatible NGPON2/G-PON system is proposed. Cost efficient and reliable system is proposed as required in next generation access networks. Data, audio and video are sent over TWDMPON/GPON and diverse linear polarized modes are analyzed. Integration of two diverse standards that can work on same feeder fiber or ODN without any extra deployment of fiber is presented. Q factor along with BER is evaluated in the system for different link lengths, and different intensity profiles i.e. LP mode profiles.

3.2 PRINCIPLE OF OPERATION

For the accomplishment of work, a pseudo random bit sequence generator for providing bit tributaries of 2^{7-1} period is incorporated in the system for investigation of high bit rate in the proposed system. Random bits from PRBS are after that given pulse shaping by linecoder such as non-return –to-zero (NRZ). Optical beams are produce by CW laser and launched power for diverse standards is different. Launched power of 10 dBm incase of Gigabit PON and again 10 dBm for NGPON2. In order to convert the pulse shapes into light signals, a MZM modulator is placed which gets derive from NRZ and CW laser. Extinction ratio of MZM control or decides the output amplitude of the pulse. A linearly polarized mode generator is placed after MZM for generating different intensity profiles for TWDM/GPON. Variation in “azimuthal” and radial number of LP mode, generates diverse intensity profiles. After completing the task of conversions, signals are now coupled to fiber optic and bi-direction optical fiber is used in the work.

A circulator is employed to control the signals in diverse directions and works on n+1 principle i.e. signal enters from port one and leave from port two and signal fed into fiber from port two, leaves from port 3. Four channels of NGPON2 and a channel of Gigabit PON are made to fall at multiplexer and later these five signals are combined to provide one multiplexed signal that consists of TWDM PON, GPON and video signals. A few mode fiber of link length 25 km is incorporated between transmitter and receiver. Optical distribution network is reused for back compatible TWDM-GPON and passive splitter is used to divide signal channel into multiple. Amplitude degradation rate of the fiber is 0.2 dB/km and total loss for 25 km is calculated as 5 dB. Insertion loss of each splitter is 1.5 dB and signal is divided into 5 ONU as depicted in Figure 3.1. At receiver, direct detection is working for the both PON standards but signal first made to fall at LP mode selector followed by photo-detector, low pass filter. Detected signal then sent to each optical network unit for analysis of BER.

Mode number of Linearly polarized modes are calculated from the expression (1)

$$\text{Mode number} = n+2m-1$$

Where,

n= azimuthal number

m= Radial number

Linearly polarized modes are of two types and are investigated for PON in this work.

Lower order modes

Higher order modes

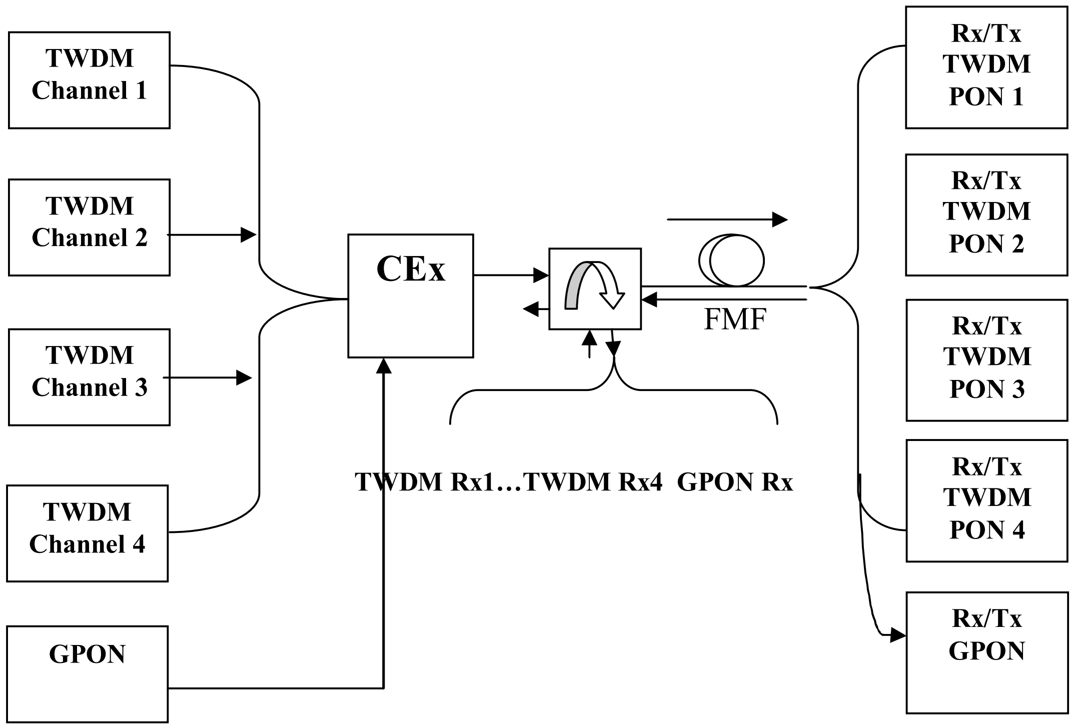


Figure 3.1 Block diagram of performance enhanced backward compatible co-existed NGPON2/GPON system

3.3 SIMULATION SETUP

3.3.1 MDM BASED BACKWARD COMPATIBILITY OF TWDM-PON WITH GPON AND RF VIDEO

The simulation setup of proposed 40 Gbps NGPON2 with video overlay in integration with 2.5 G Gigabit PON is depicted in Figure 3.2. TWDM has different four channels each at diverse wavelength and bit rate of 10 Gbps/channel. For pay as you grow features, four channels of TWDM PON are multiplexed with GPON channel and video overlay is also combined with these standards. It is observed that no optical amplifier is considered in this work. Each TWDM PON and GPON channel provided a diverse linearly polarized mode for MDM. Both the aforementioned standards are combined with a coexistence mux (CEx).This employment technique provides well-organized system arrangement and augmented reliability for service providers and moreover takes the benefit of ‘pay as you grow’ feature.

Internal structure of optical line terminal for NGPON2/GPON is depicted in Figure 3.3. Optical line terminal located in central office consists of five important components such as PRBS for generation of serial bit stream at 10 Gbps per channel for TWDM and

2.5 Gbps for Gigabit PON channel. Serial data stream is followed by pulse shaper which provide digital logic level to bits and basic linecoder NRZ is used in the work.

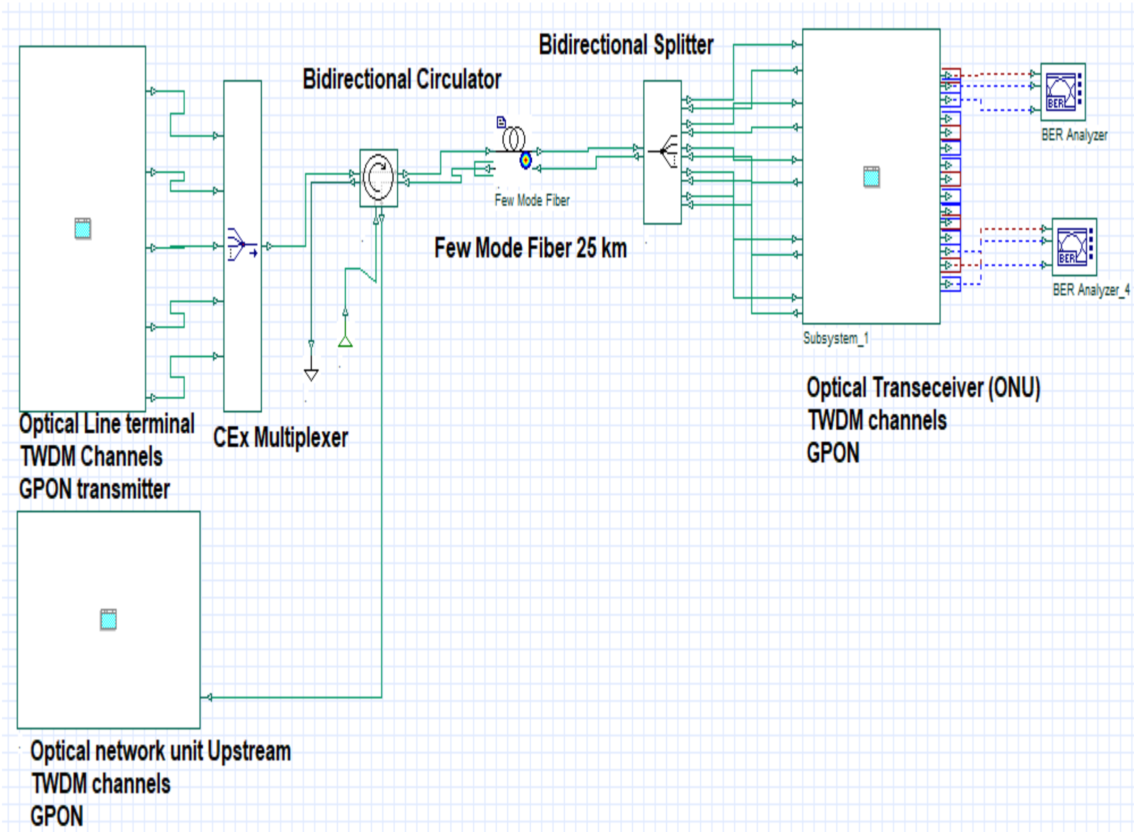


Figure 3.2 Simulation setup of proposed coexisted backward compatible NGPON2/GPON

MZM modulator has two input ports and getting derive from CW Lased and linecoder. Input power of 10 dBm is selected in case of gigabit PON and TWDMPON per channel. Extinction ratio of 30 dBm is considered and four TWDM channel are joined by using WDM multiplexer. Further these four channels combined with gigabit PON channel and video overlay by using CEx. Bandwidth of MUX is set to be double the data rate and 20 GHz is taken and wavelength spacing of 1 nm is fixed among different WDM channels. GPON works on wavelength 1490 nm and for TWDM PON, wavelengths of L band are used according to their operating assigned window according to standard given by ITU. All wavelengths of coexisting system is given for TWDM as λ_1=1596 nm, λ_2=1597 nm, λ_3=1598 nm and λ_4=1599 nm and video signal is overlaid on fourth channel. For gigabit PON, wavelength of 1490 m is considered at 2.5 Gbps. Linearly polarization generator place after MZM for each channel that change the intensity profile of modes. LP mode are used for NGPON2 are LP01, LP11, LP21, LP12 and for gigabit PON, LP13 is used.

Legacy optical distribution network which was used for XGPON, EPON/GPON is used in the work to save cost and to remove complexity.

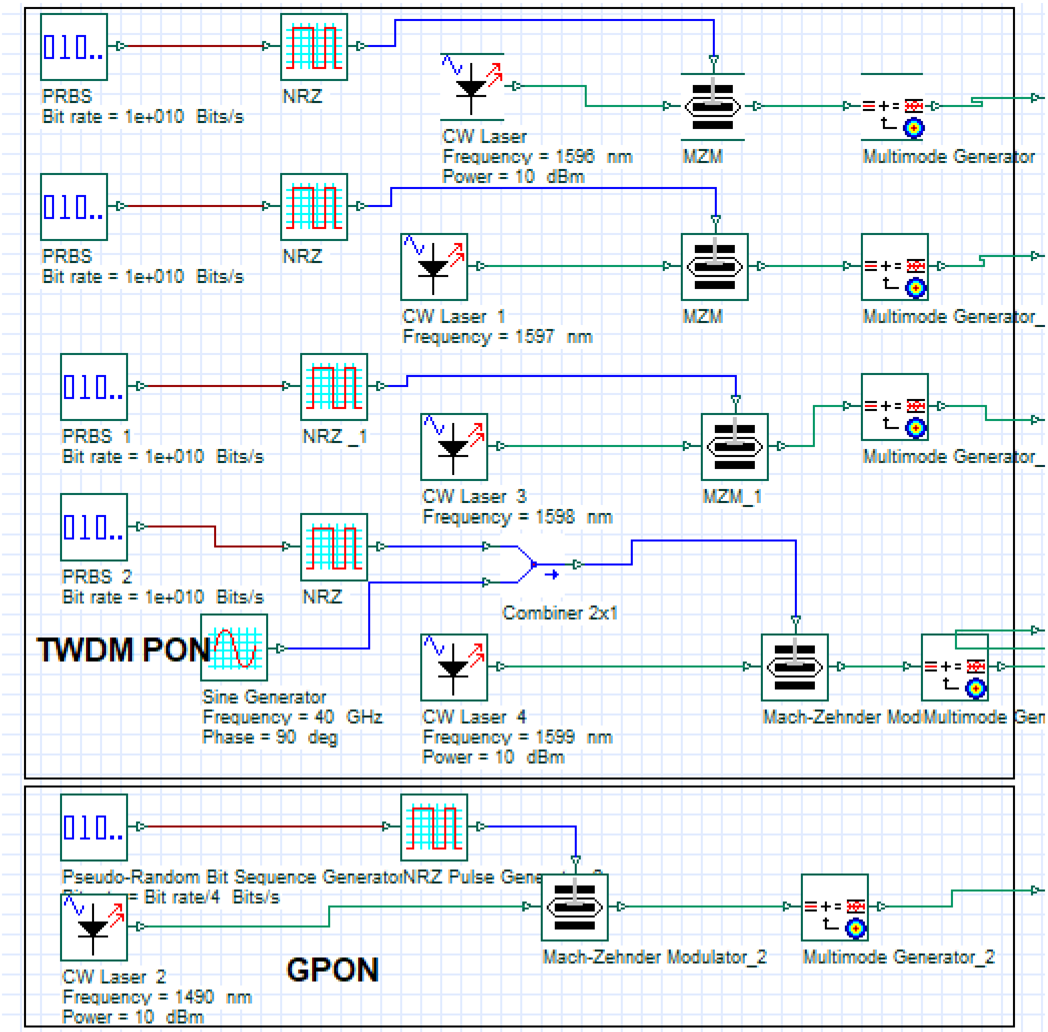


Figure 3.3 Internal structure of optical line terminal

In order to accomplish uplink transmission of integrated standards, transmitter is placed in ONU. For NGPON2, a bit stream of 10 Gbps per channel and power of 5 dBm is given. Bit stream is modulated with NRZ pulse generator through MZM modulator as shown in Figure 3.4. Same is true for GPON except data rate. It has bit rate if 1.25 Gbps in uplink. All wavelengths of coexisting system is given for TWDM in order to done uplink transmission as λ_1=1524 nm, λ_2=1525 nm, λ_3=1526 nm and λ_4=1527 nm and for gigabit PON, 1310 nm is taken. Upstream signals then travel through 25 km FMF and in this work, MUX/DEMUX are located in OLT for making very less changes in conventional PON system. Receiver consists of PIN and LPF for 4 TWDM and a GPON system as shown in Figure 3.5. For the performance evaluation of the system, BER diagram is checked along with Q factor, BER of system.

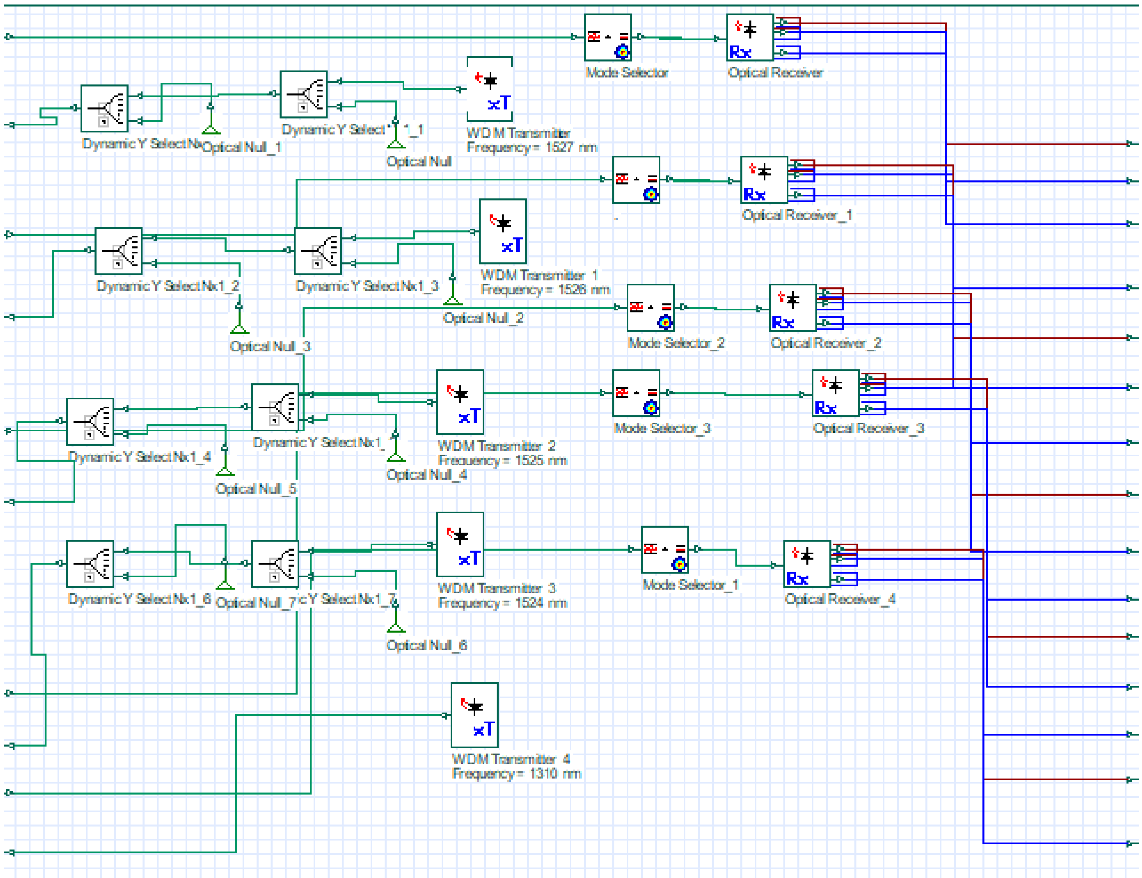


Figure 3.4 Internal structure of optical network unit downstream

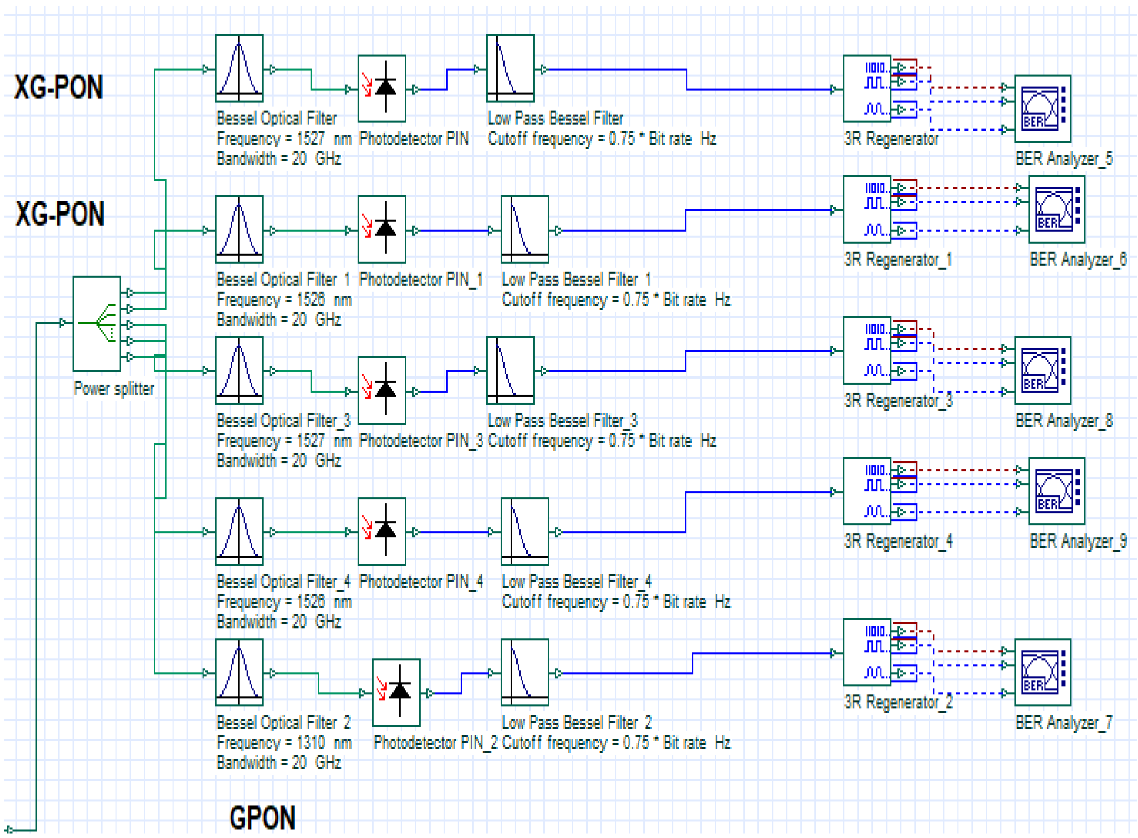


Figure 3.5 Internal structure of optical network unit of upstream

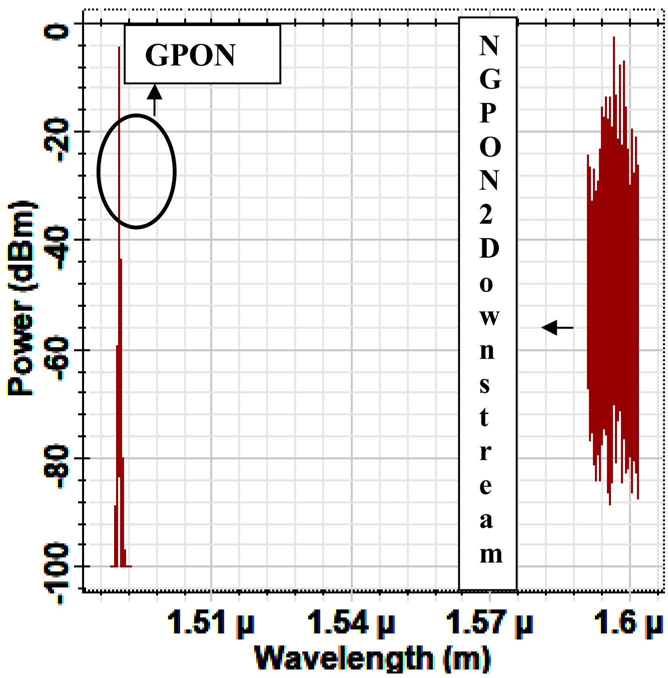
CHAPTER 4

RESULTS AND ANALYSIS

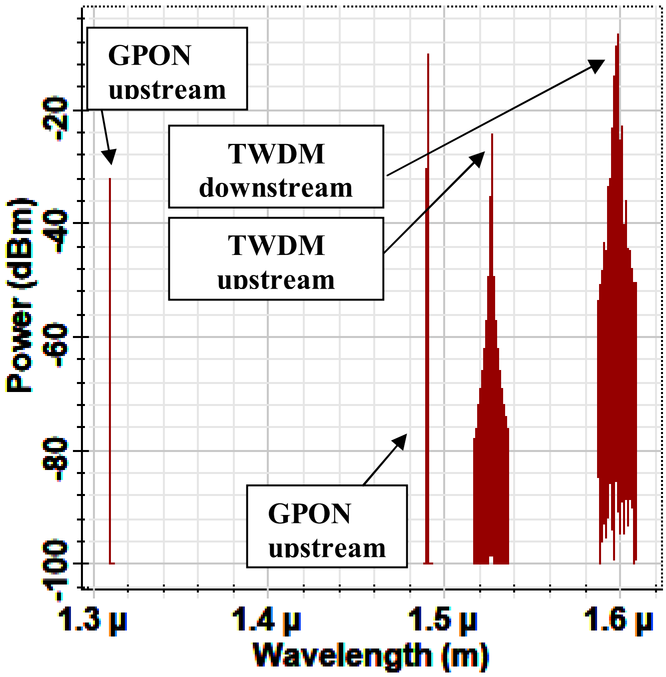
In this work, performance enhancement and investigation of coexisting integrated backward compatible next generation passive optical network and gigabit passive optical network has been done. Work is accentuated on the analysis of mode division multiplexing by incorporating diverse intensity profile is carried for TWDM PON and GPON. Video overlay and triple play support of PON is also evaluated over the same transmission medium length for both PON standards.

Figure 4.1 (a) represents the output of optical spectrum analyzer for total carrier signals in downstream i.e. for TWDM and GPON signals from optical line terminal to premises located ONU. It is clear from the figure that GPON carrier signal is at 1490 nm with power level of -5 dBm and TWDM PON's 4 channels are also represented in figure for downstream. NGPON2 channels are cantered in L band and wavelengths are λ_1=1596 nm, λ_2=1597 nm, λ_3=1598 nm and λ_4=1599 nm and video signal is overlaid on fourth channel. Power at each L band TWDMPON channel is -3 dBm.

Figure 4.2 (b) depicts the output of OSA for total carrier signals both in downlink and uplink. Total 10 wavelengths are used for both PON standards. Total 4 downstream and 4 upstream wavelengths are for TWDMPON and 1 downstream as well as 1 upstream wavelength for GPON.



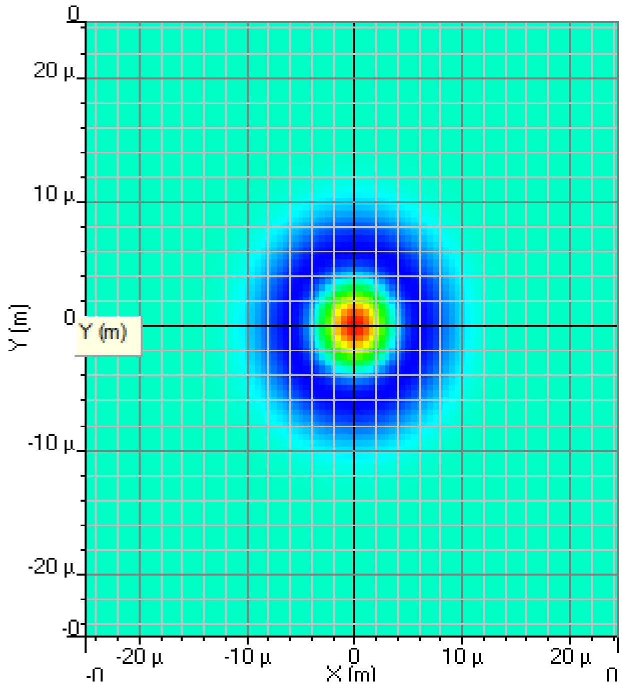
(a)



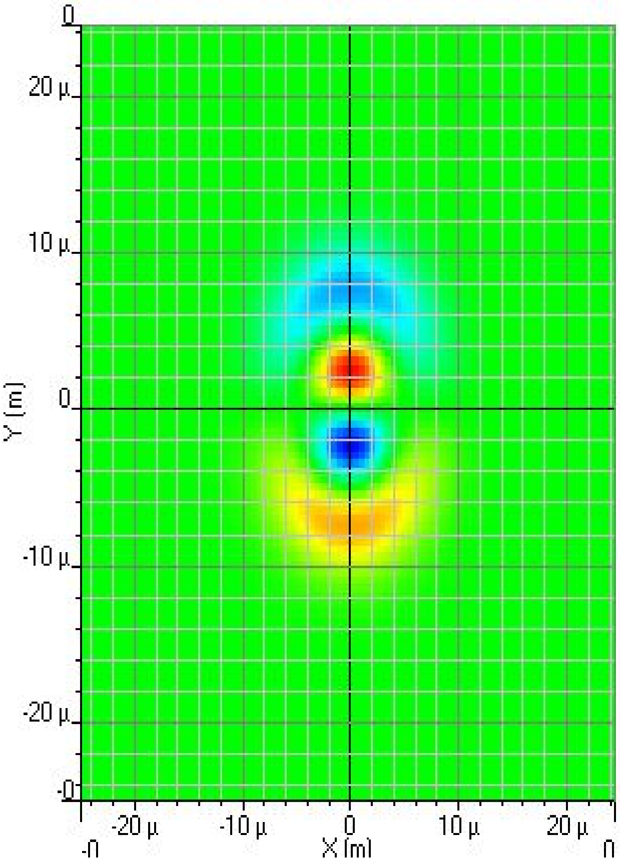
(b)

Figure 4.1 Optical spectrums of carrier signals for (a) downstream only (b) total wavelengths in DS and US

Wavelengths in downstream for TWDMPON and GPON are mentioned above and for upstream, GPON uses 1310 nm wavelengths and NGPON2 has wavelengths at λ_1=1524 nm, λ_2=1525 nm, λ_3=1526 nm and λ_4=1527 nm.

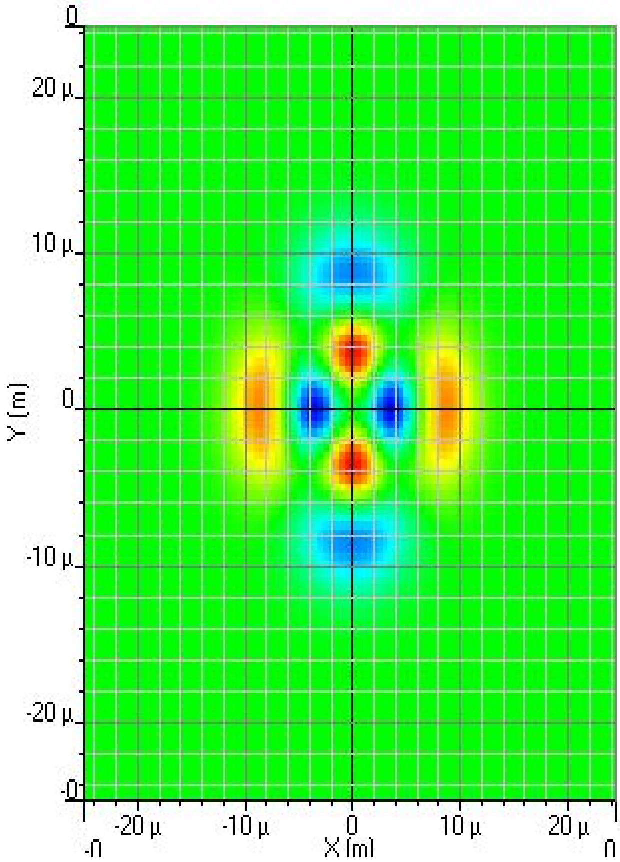


(a)



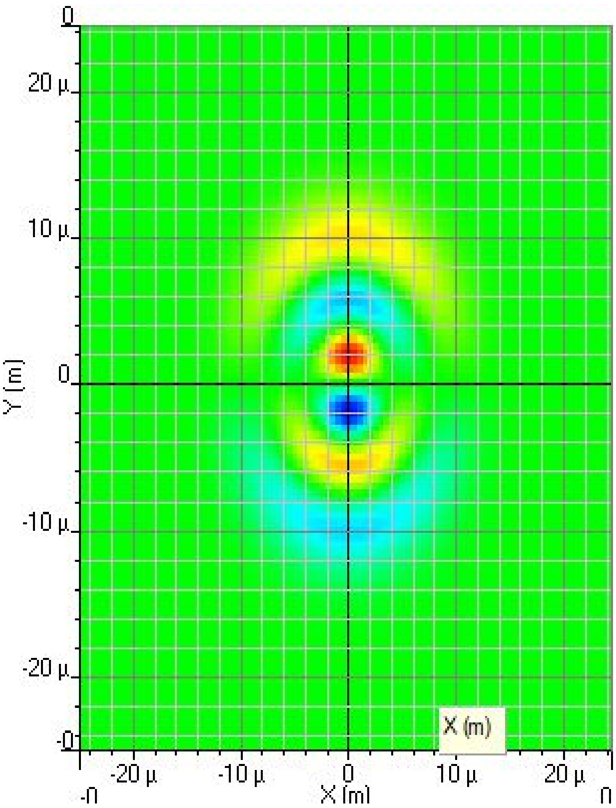
0
20 µ
10 µ
0
-10 µ
-20 µ
-0
Y [m]
-20 µ
-10 µ
0
10 µ
20 µ
-0
X [m]
0

(b)

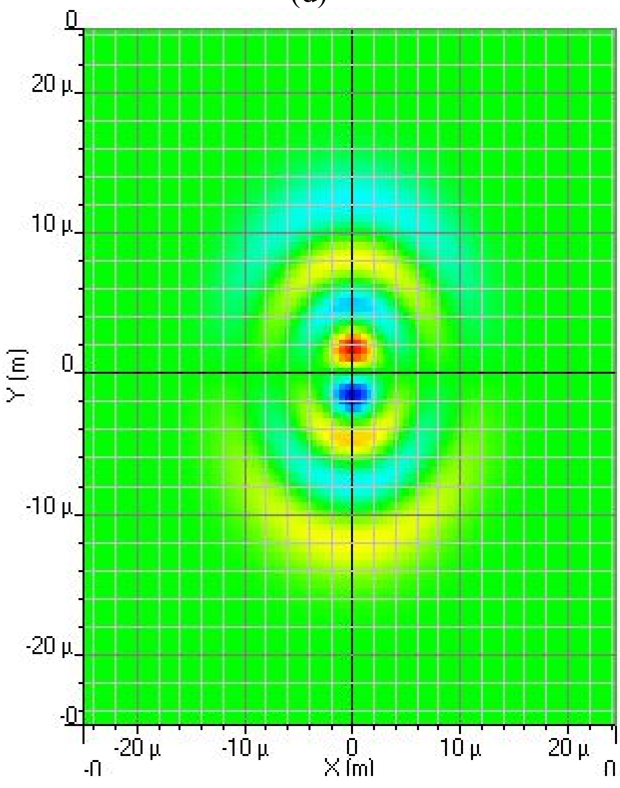


0
20 µ
10 µ
0
-10 µ
-20 µ
-0
Y [m]
-20 µ
-10 µ
0
10 µ
20 µ
-0
X [m]
0

(c)



(d)

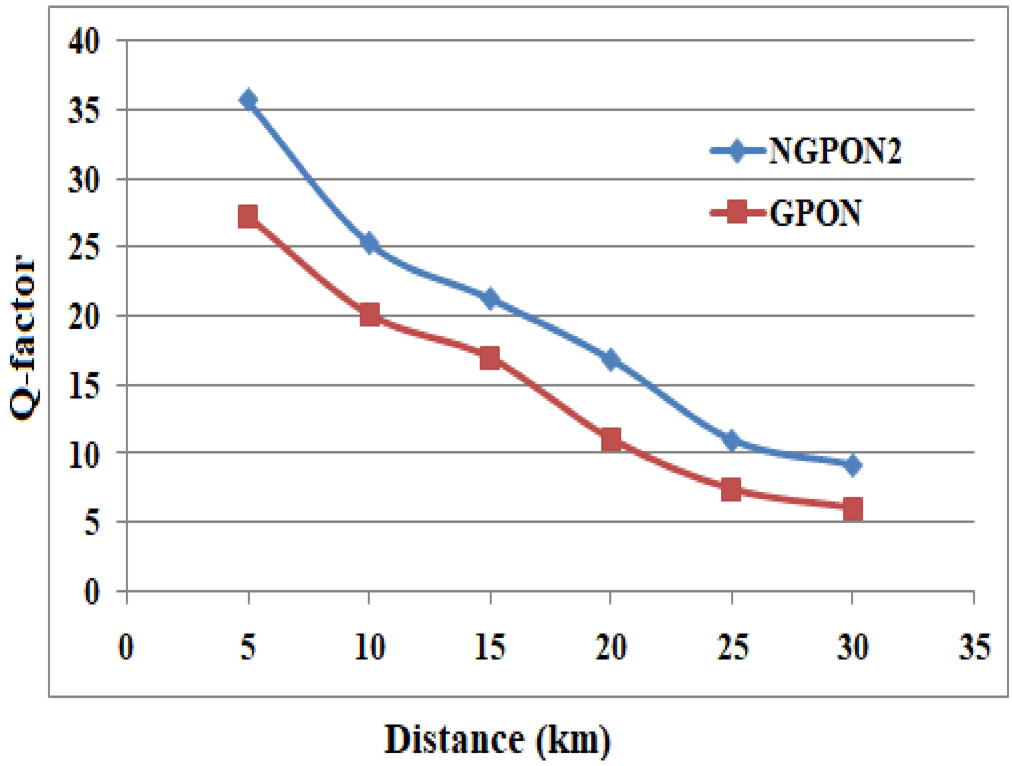


(e)

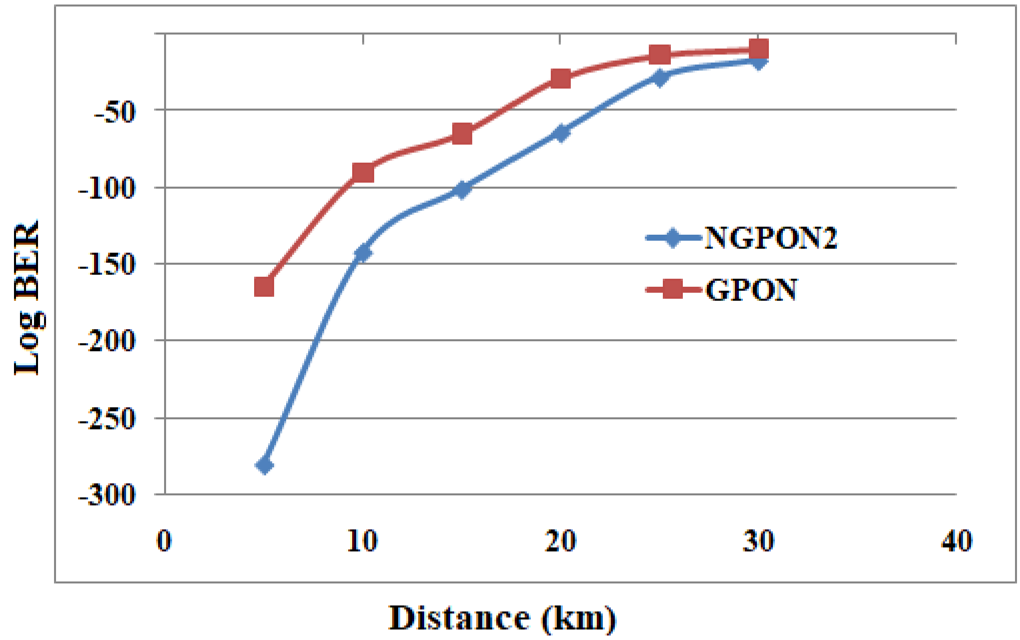
Figure 4.2 Mode profiles of LP modes for TWDM PON (a) LP01 (b) LP11 (c) LP21 (d) LP21 and GPON (e) LP13

After representation of upstream and downstream wavelengths, depiction of mode division multiplexing based diverse linearly polarized modes has been done. LP modes are varied in intensity profile by varying its value of n and m which are discussed in equation (1). Figure 4.2 (a) depicts the mode profile of LP01 mode which is referred as basic profile. It has one peak of n and one radial circle of m. Similarly mode profile of diverse LP modes is shown in Figure 4.2.

Investigation of the proposed system has been carried out by varying distance from 5 km to 30 km between OLT and ONU. Both the PON standards are running on same optical fiber. Few mode fiber is considered due to propagation of modes. Moreover, FMF has fewer losses than multimode fiber because it allows only few modes to pass according to boundary conditions. Figure 4.3 depicts the plot of distance versus Q factor of the NGPON2 and GPON. A comparison has been established between these two standards. It is evident that attenuation increases as length of FMF prolongs and Q of TWDM PON and gigabit PON decreases. But it is perceived that for entire distance range, NGPON2 surpasses the performance of GPON due different wavelengths, time and mode profiles. In GPON, a single wavelength is there and prone to noises as seen from the results. Therefore, NGPON2 is proved better than GPON systems.



(a)



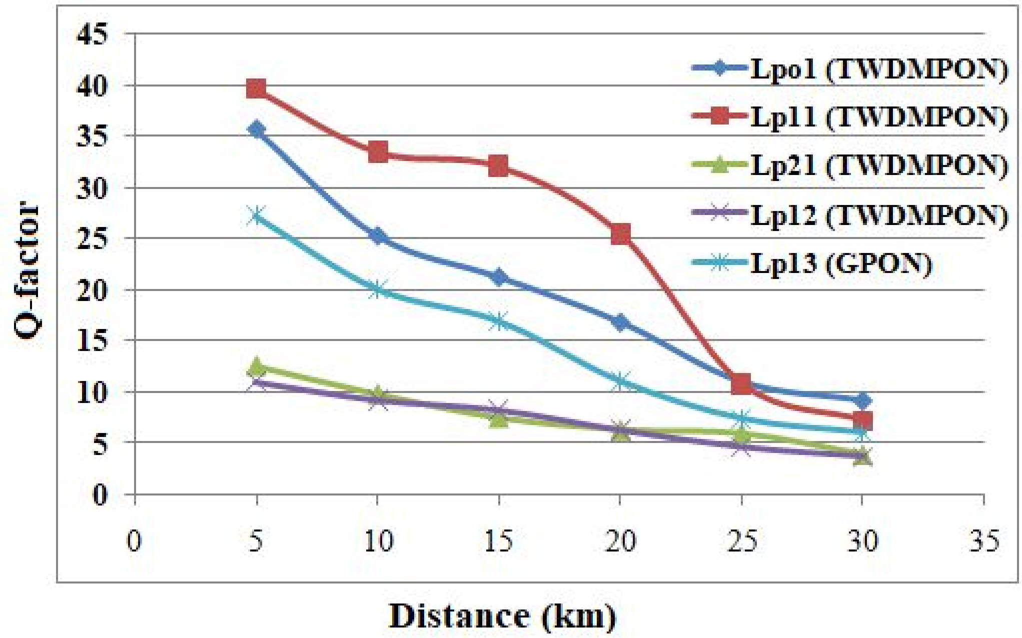
(b)

Figure 4.3 Comparison of NGPON2 and GPON in backward compatible system in terms of (a) Q factor (b) Log BER at diverse distances

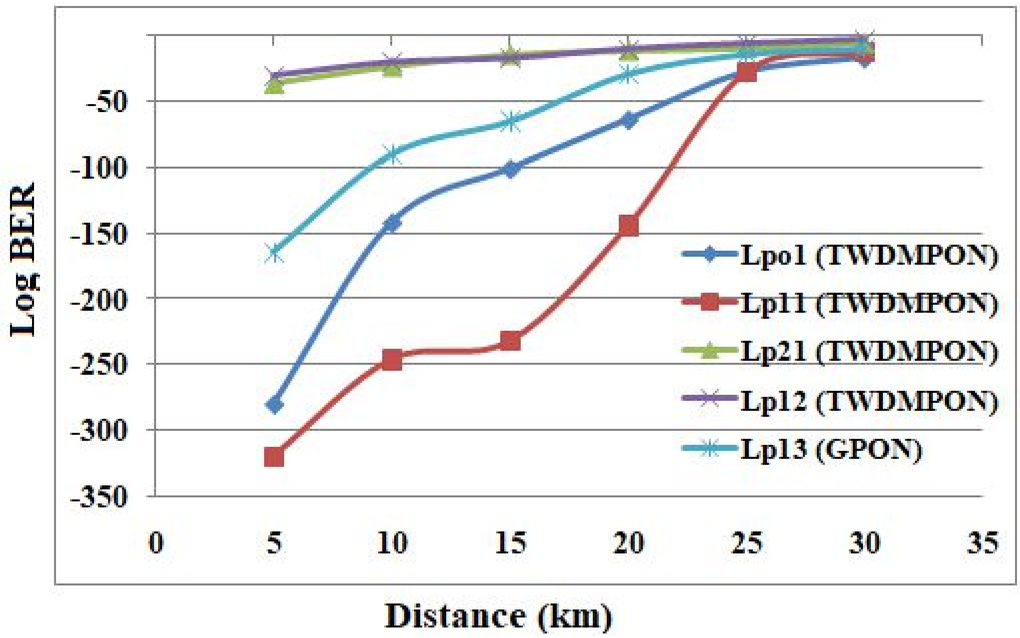
Investigation of the proposed system in terms Log BER has been done changing link length from 5 km to 30 km between central office and optical network unit. Transmission medium i.e. FMF is same for TWDM PON and GPON.

Figure 4.3 (b) depicts the plot of distance versus Log BER of the NGPON2 and GPON. A comparison has been established between these two standards by considering errors rate. Result reveals that amplitude degradation increases as length of FMF increases and Log BER of TWDM PON and gigabit PON increases. It is observed that NGPON2 performs better than gigabit PON in terms of Log BER at every distance.

Performance of diverse LP modes is an important work to study for integrated backward compatible NGPON2/GPON systems. As diverse LP modes are assigned to each channel of TWDM PON and GPON, their performance also varies depending upon mode profile or mode number. Total five LP modes are used in this work, 4 LP modes are for TWDM PON and one for GPON. Performance of each mode is studied at different distances and evaluated in terms of Q factor. Figure 4.4 (a) depicts the system performance for LP modes. It is evident that performance of LP mode number 11 is maximum and highest Q is attained at this mode profile. Performance of LP11 mode is followed by first order mode LP01 and further followed by LP13 (GPON). Least Q is provided by LP 12 mode. Thus LP11 is optimal mode profile for proposed system.



(a)

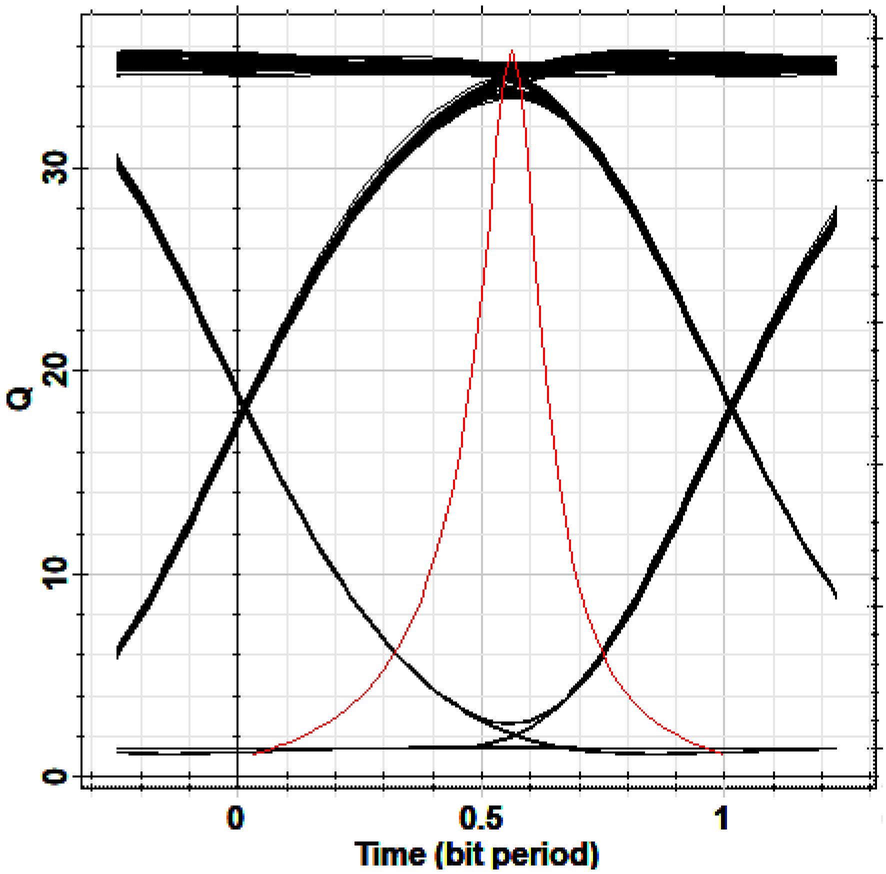


(b)

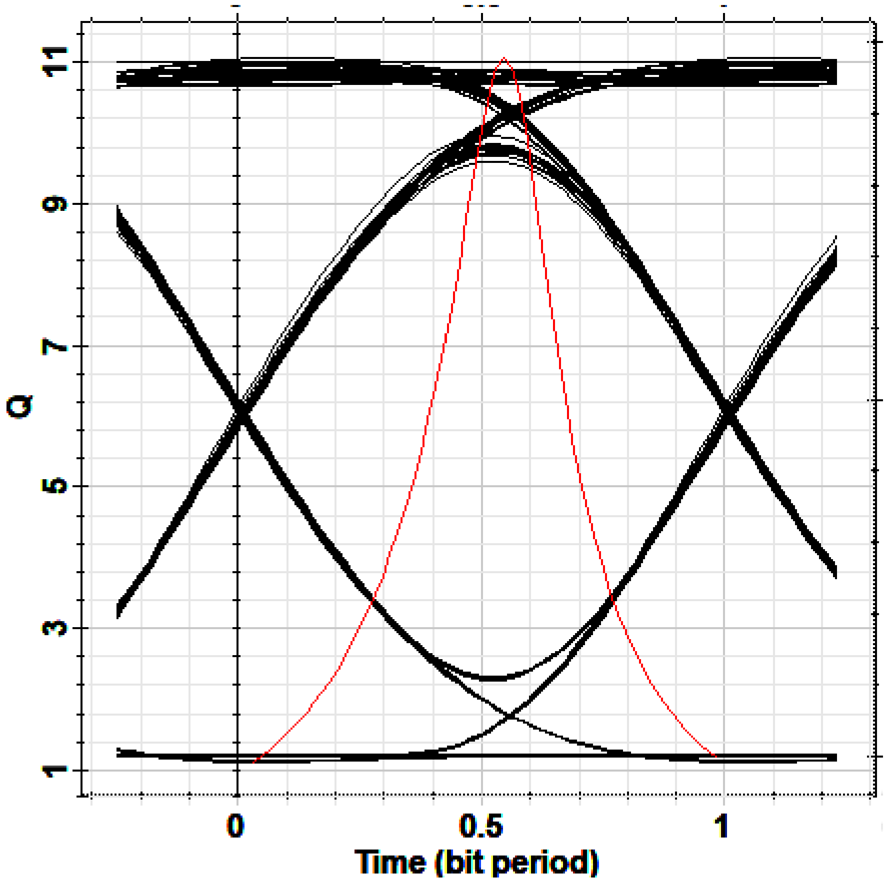
Figure 4.4 Performance analysis of different order modes in proposed system for (a) Q factor (b) Log BER at varied distances

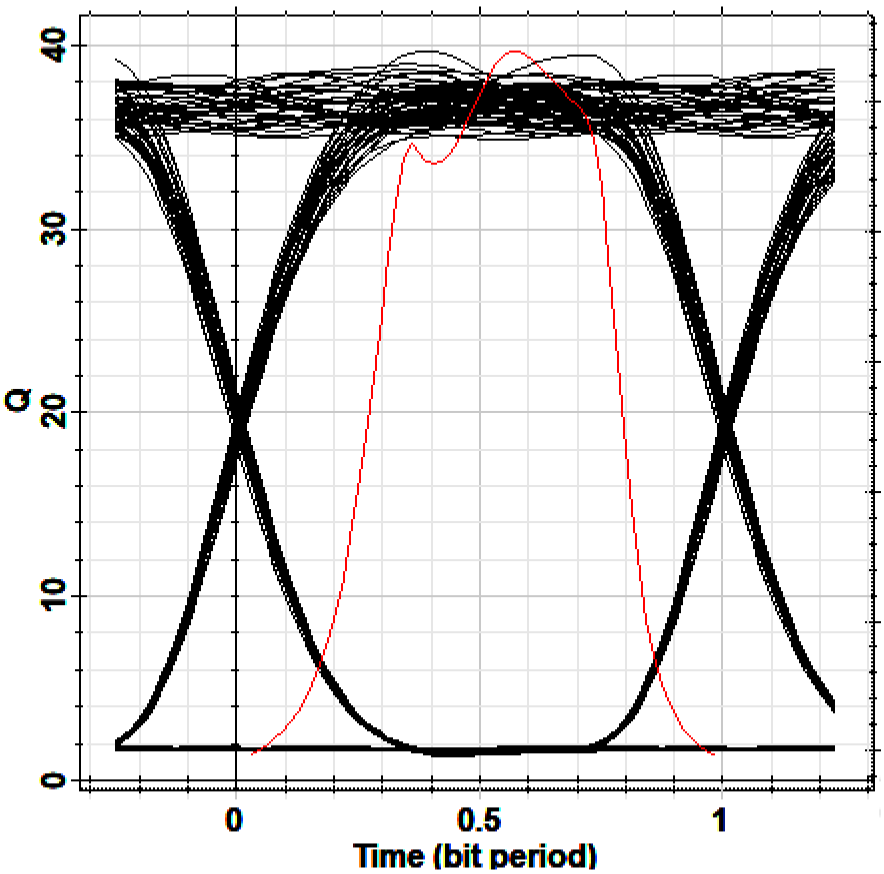
Performance of each mode is studied at different distances and evaluated in terms of Log BER. Figure 4.4 (b) represents the system performance for diverse LP modes. It is evident that Log BER of LP mode number 11 is least and minimum errors are observed at this mode profile. Log BER of LP11 mode is followed by first order mode LP01 and further followed by LP13 (GPON). Highest Log BER is provided by LP 12 mode. Thus LP11 is optimal mode profile for proposed system in tems of Log BER also.

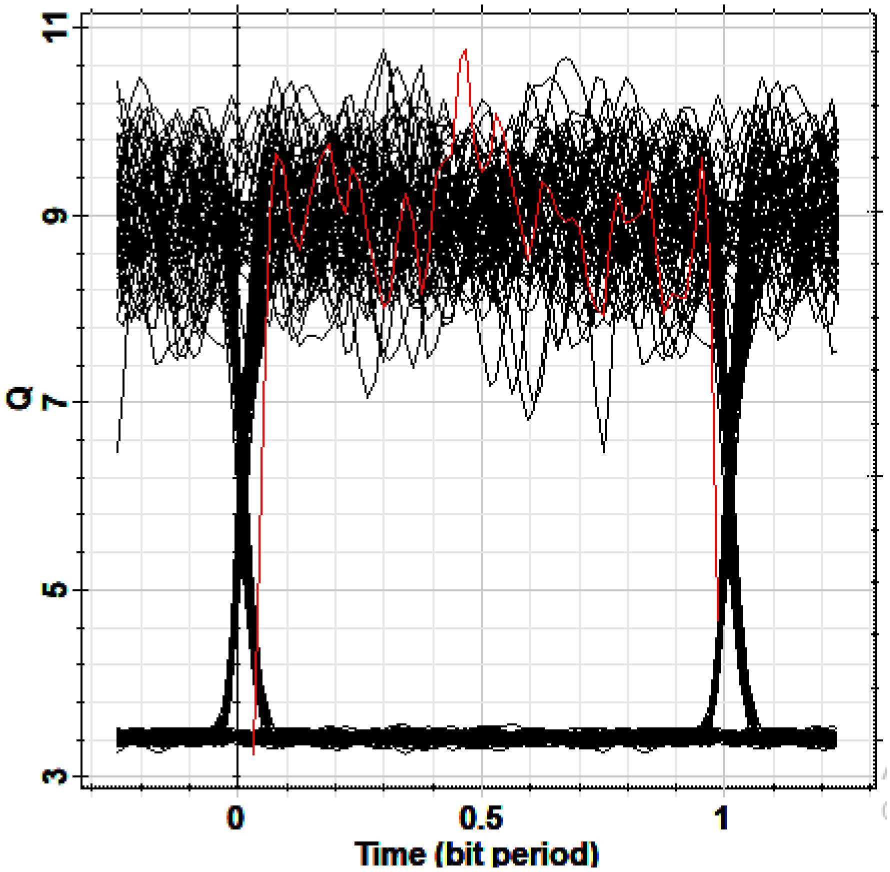
Eye diagram is a performance decisive component that provides Quality of and errors of the received signals. Eye opening decides the value of Q and BER such that more eye opening provides better Q and less BER. Moreover values of jitter are lower if eye opening is more. Eye diagrams at 5km and 25 km for TWDM PON and GPON systems are represented in Figure 4.5. Wide eye opening and high Q factor is obtained at 5 km in all case but Q decreases abruptly when distance increases to 25 km. Figure 4.5 (a) and (b) represents the eye diagrams of linearly polarized mode 01 i.e. TWDM PON channel 1. Quality factor of 35.76 is observed at 5 km and 11.05 on 25 km. Similarly, Quality factor of 39.64 is observed at 5 km and 10.77 on 25 km for LP11 as shown in Figure 4.5 (c) (d) and (e) (f) Quality factor of 12.59 is observed at 5 km and 6.01 on 25 km. Mode LP12 provides Q of 11.03 and 3.7 at 5 km and 25 km respectively as depicted in Figure 4.5 (g) (h). GPON system having LP13 mode has Q 27.78 at 5 km and 6.06 at 25 km as given in (i) (j) respectively.



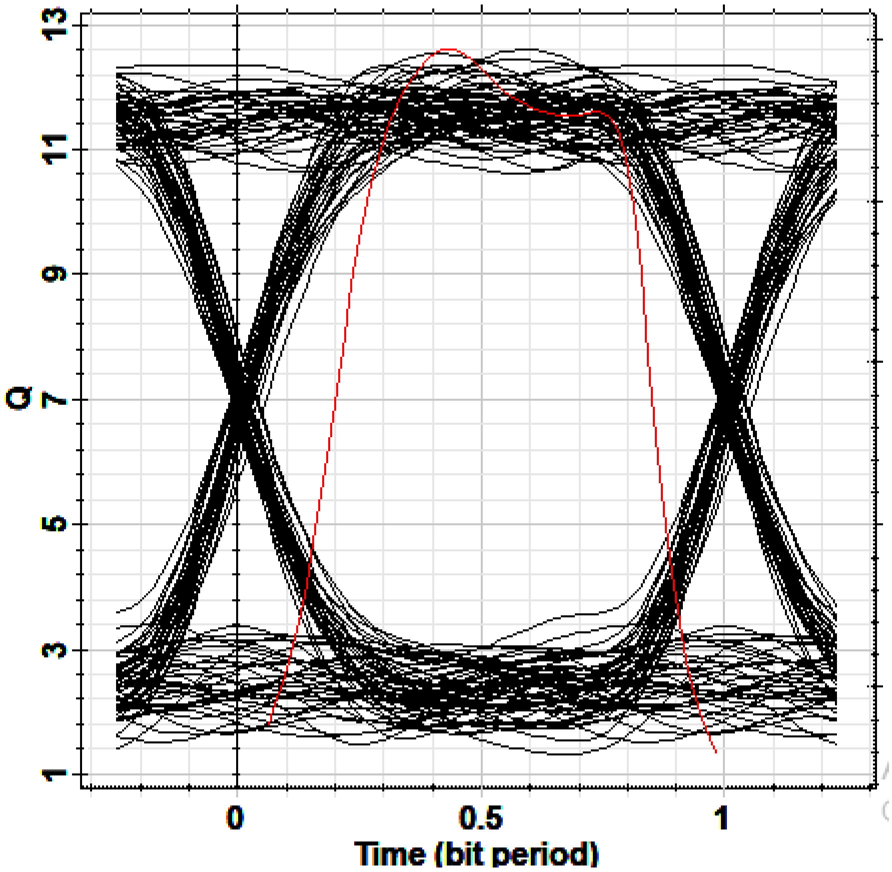
(a)


Q
11
9
7
5
3
1
0
0.5
1
Time (bit period)
(b)

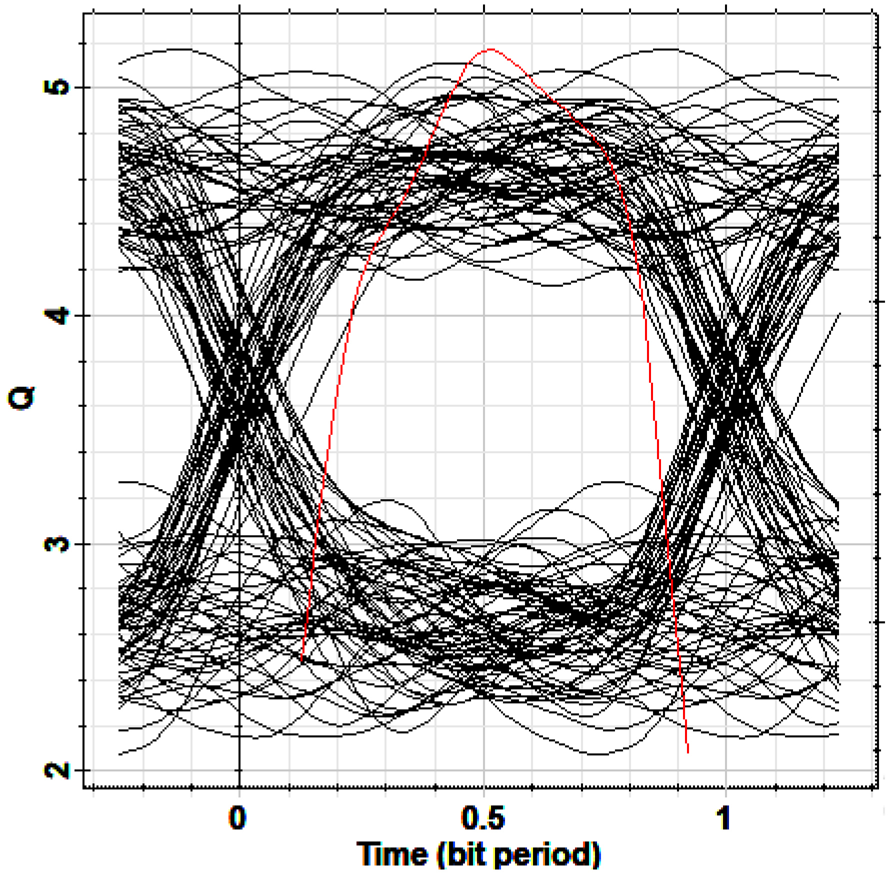

Q
40
30
20
10
0
0
0.5
1
Time (bit period)
(c)



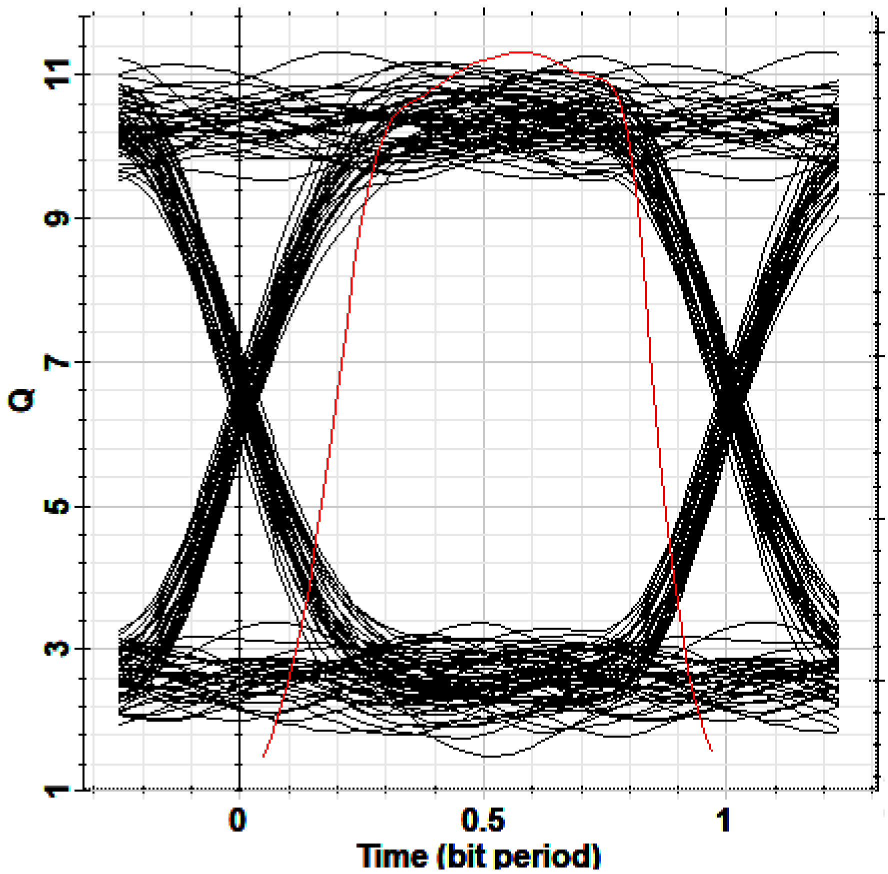
(d)



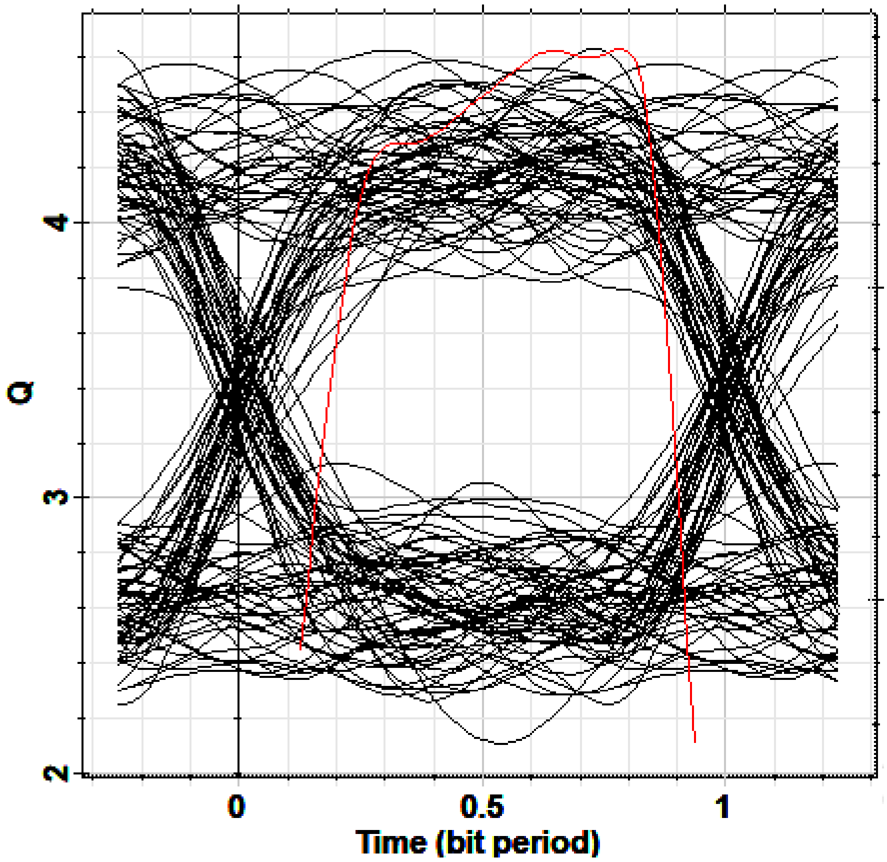
(e)



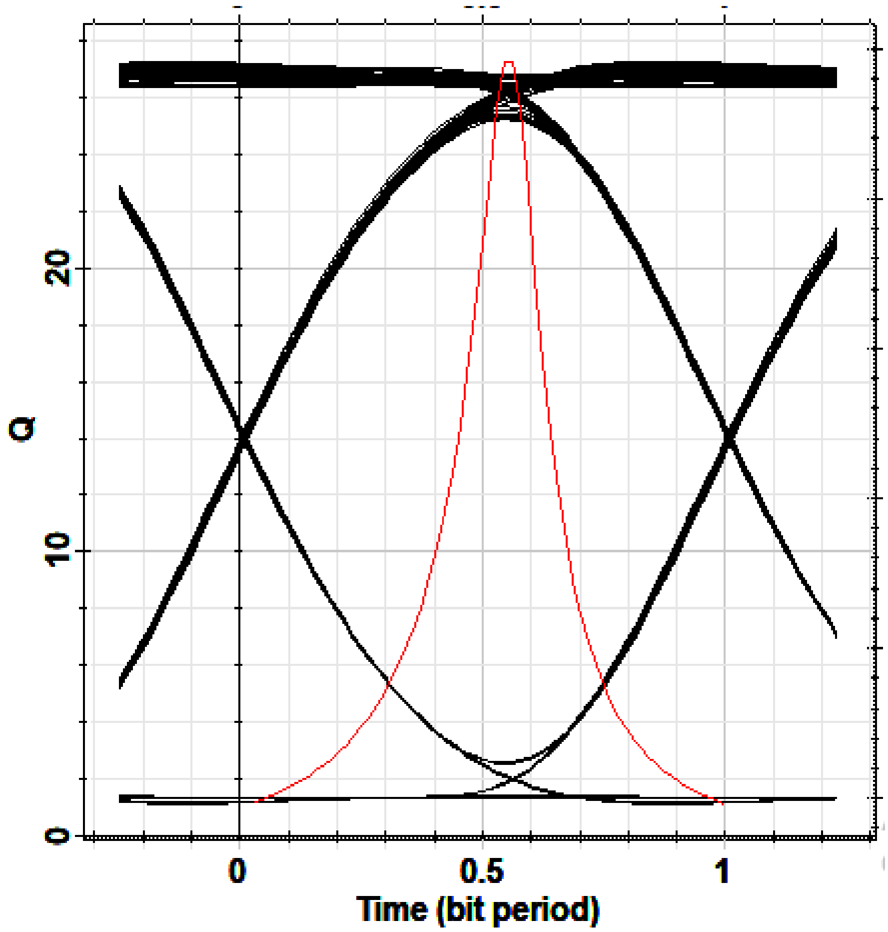
(f)



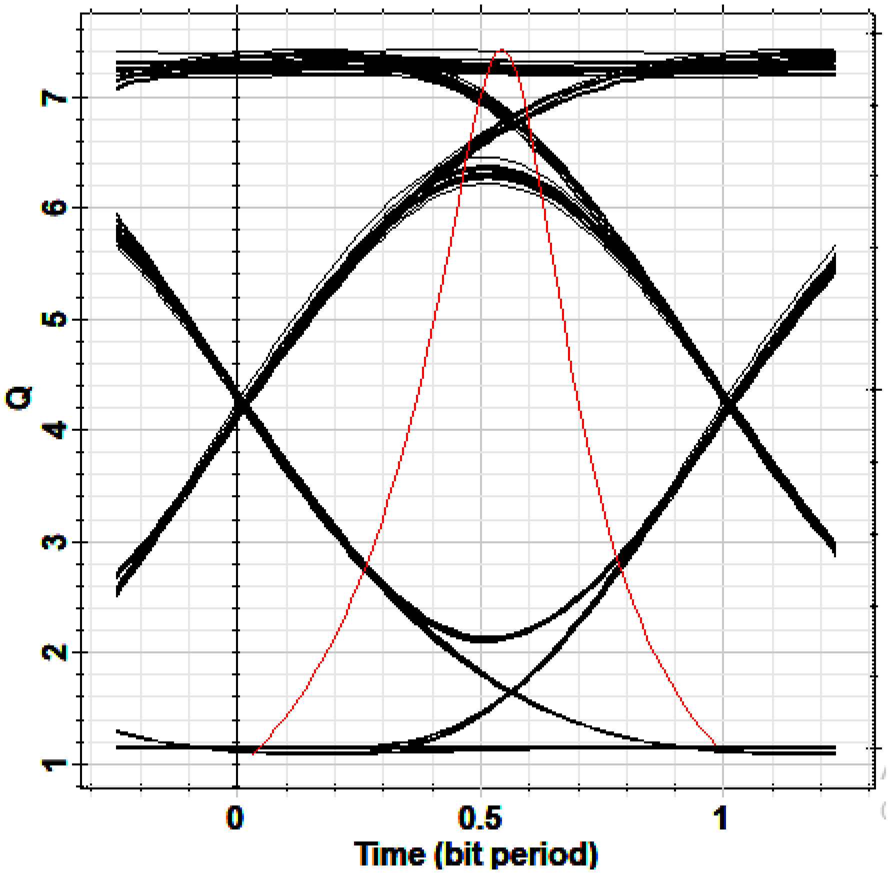
(g)



(h)



(i)



(j)

Figure 4.5 Eye Diagrams representation for 5km and 25 km respectively for (a) (b) LP01 (c) (d) LP11 (e) (f) LP21 (g) (h) LP12 (i) (j) LP13

Table 4.1 shows the values of NGPON2 and GPON at different distances in terms of Q factor. It is observed that Q factor is highest in NGPON2.

Table 4.1 Values of Q factor versus distance

Distance (km)	NGPON2	GPON
5	35.76	27.28
10	25.39	20.13
15	21.34	16.97
20	16.92	11.07
25	11.05	7.42
30	9.26	6.06

Table 4.2 shows the values of NGPON2 and GPON at different distances in terms of Log BER. It is observed that BER is lowest in NGPON2.

Table 4.2 Values of Log BER versus distance

Distance (km)	NGPON2	GPON
5	-280	-164
10	-142	-90
15	-101	-65
20	-64	-29
25	-28	-14
30	-17	-10

Table 4.3 and Table 4.4, shows the values of different LP modes at different distances in terms of Q factor and Log BER respectively.

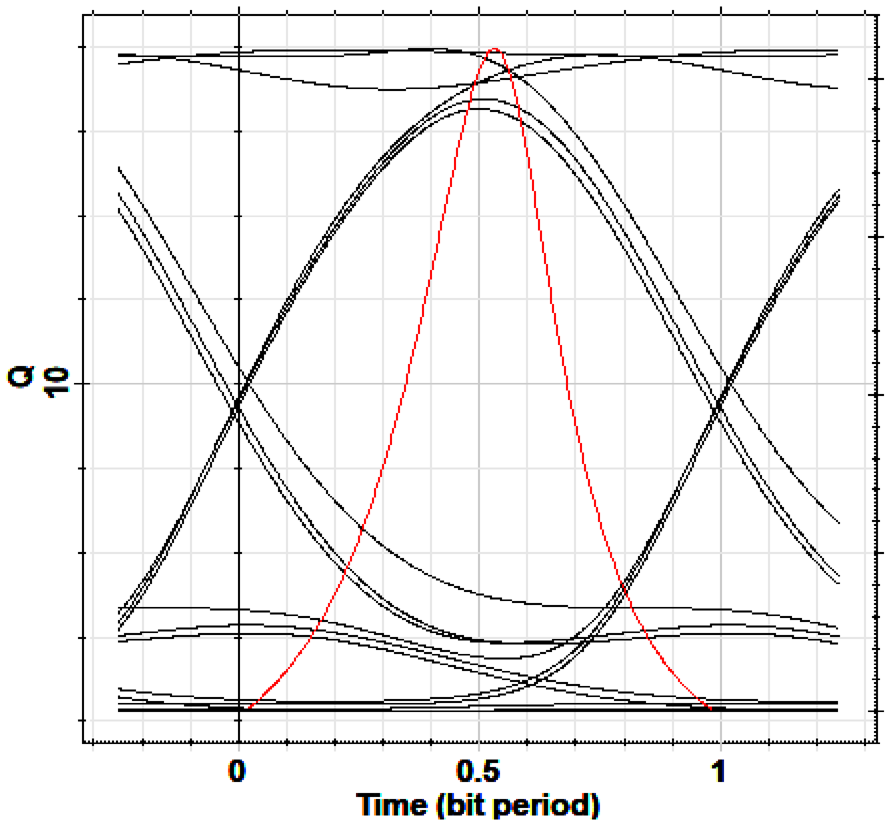
Table 4.3 Values of Q versus different distance for different LP modes

Distance (km)	Lpo1	Lp11	Lp21	Lp12	Lp13
5	35.76	39.64	12.59	11.03	27.28
10	25.39	33.51	9.85	9.24	20.13
15	21.34	32.14	7.55	8.26	16.97
20	16.92	25.48	6.38	6.28	11.07
25	11.05	10.77	6.01	4.62	7.42
30	9.26	7.21	3.96	3.7	6.06

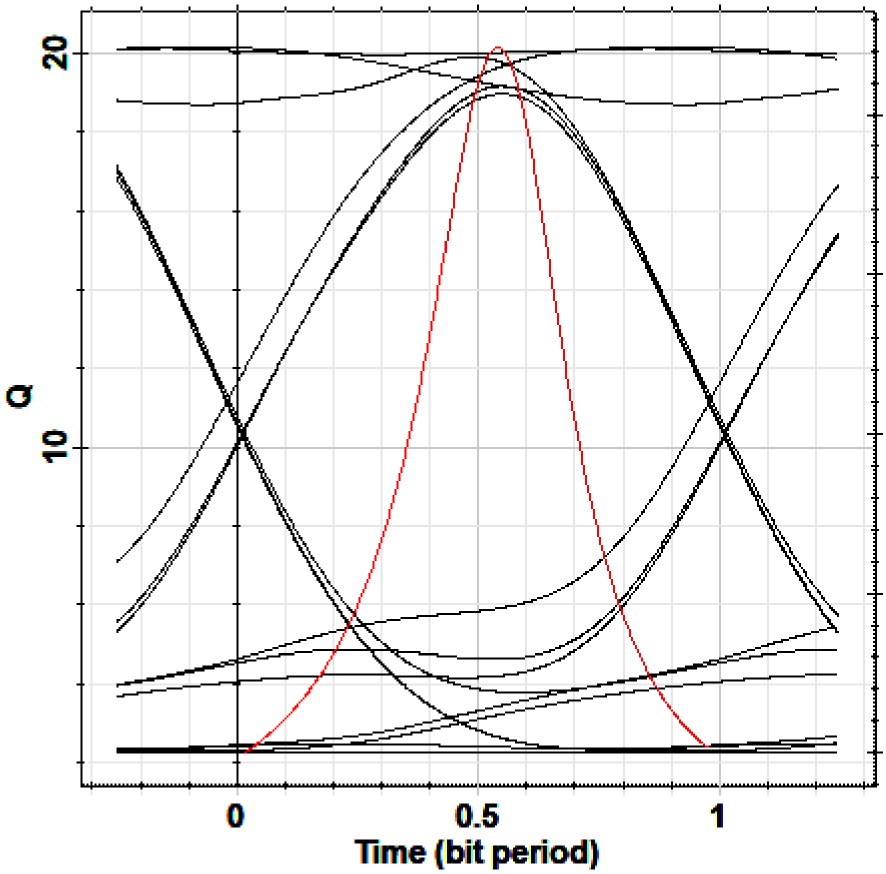
Table 4.4 Values of Log BER at different distance for different LP modes

Distance (km)	Lpo1	Lp11	Lp21	Lp12	Lp13
5	5	-280	-320	-36	-30
10	10	-142	-246	-23	-20
15	15	-101	-232	-14	-17
20	20	-64	-144	-11	-10
25	25	-28	-27	-9	-6
30	30	-17	-12	-5	-3

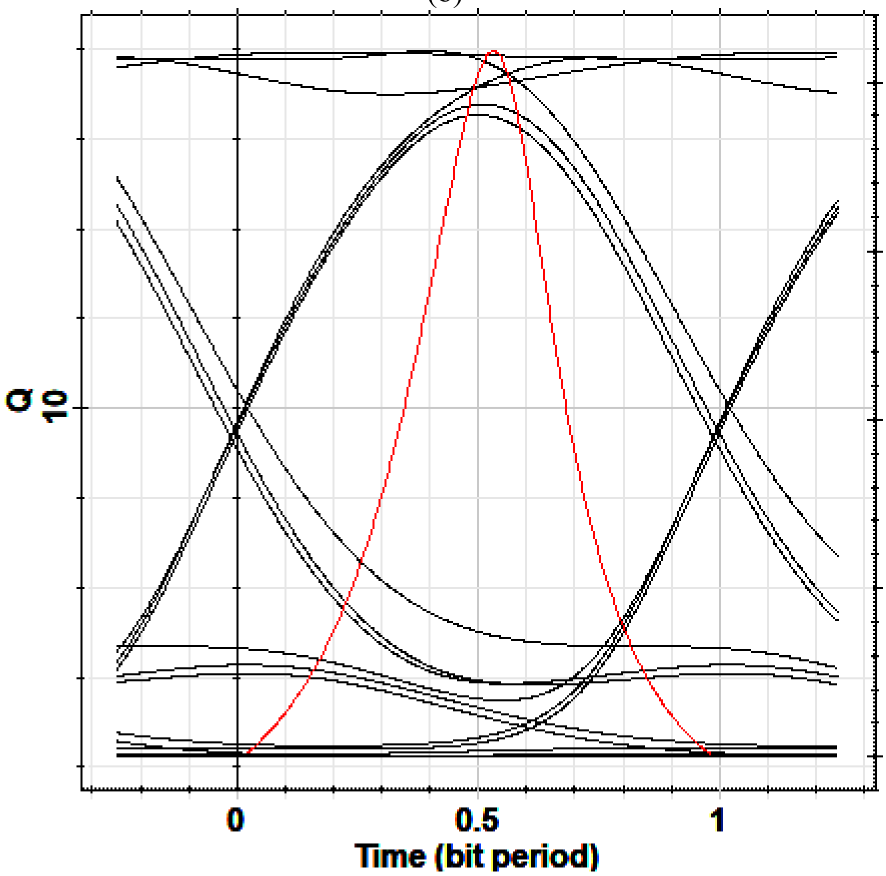
Figure 4.6 represents the Eye diagram of the system in upstream at 25 km link distance for all LP modes. Figure 4.6 (a) and (b) (c) (d) (e) represents the eye diagrams of linearly polarized mode 01, LP11, LP21, LP12 and LP13. Maximum Q and eye opening is observed in LP01 mode in upstream at 25 km.



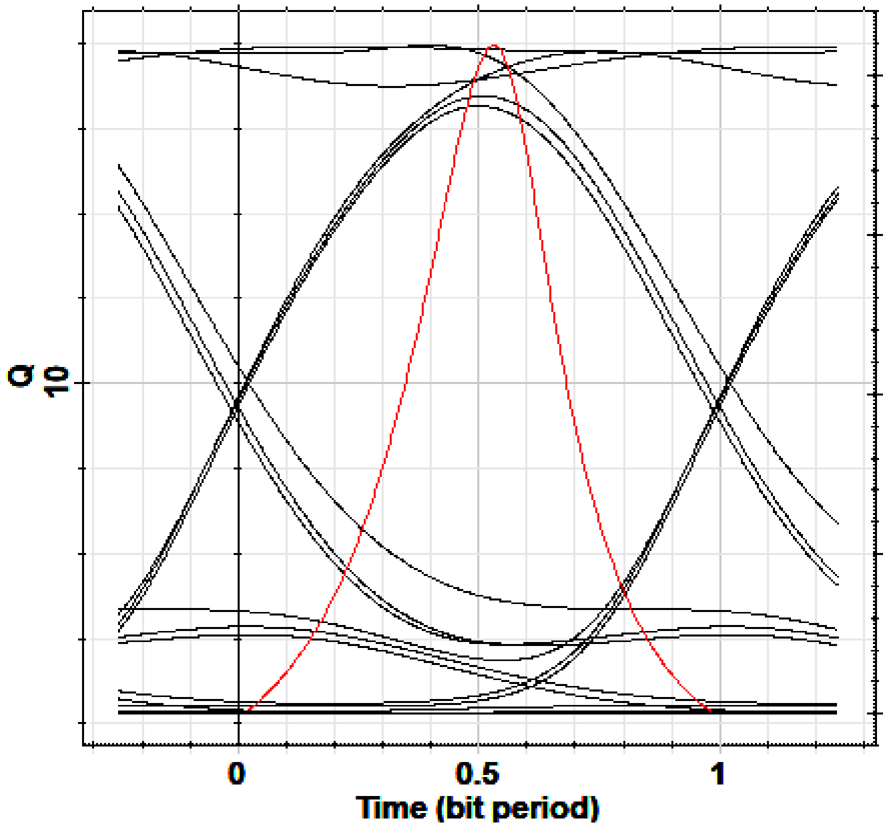
(a)



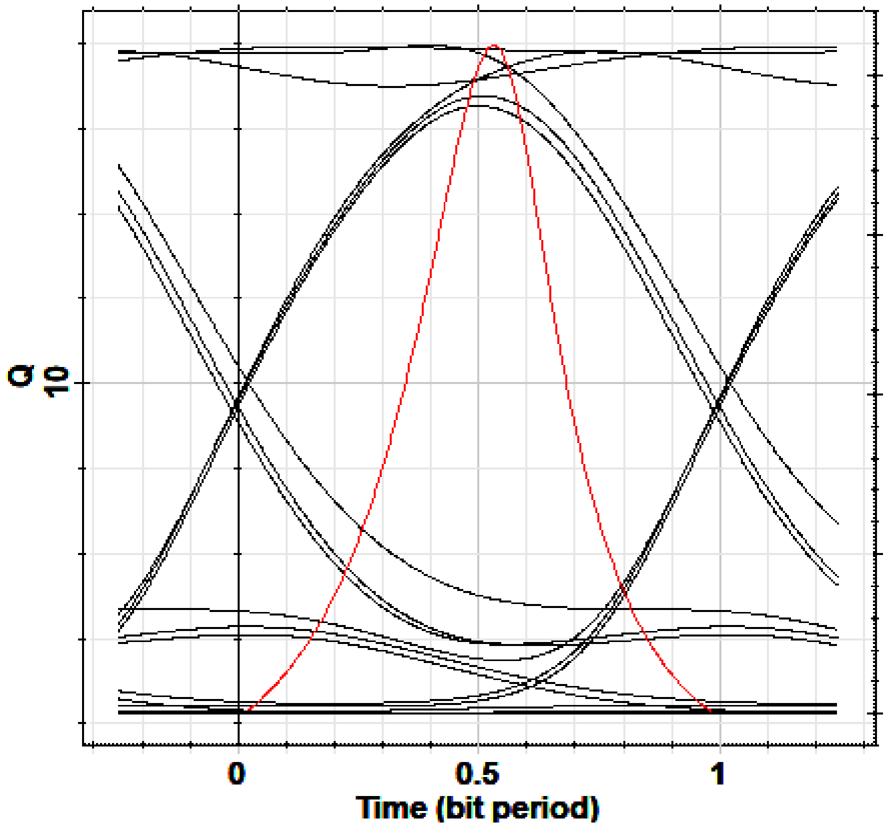
(b)



(c)



(d)



(e)

Figure 4.6 Eye diagram of different LP modes in upstream at 25 km (a) LP01 (b) LP11 (c) LP21 (d) LP12 (e) LP13

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 CONCLUSIONS

Conclusion and future scope of the work is as follows:

In this work, a coexisted backward compatible integrated NGPON2 and Gigabit PON is proposed by incorporating mode division multiplexing. Cost efficient and reliable system is proposed as required in next generation access networks and triple play services are sent over FMF by TWDMPON/GPON with diverse linear polarized modes. Proposed system is a new approach for pay as you grow services. This is a promising integration of two diverse standards that can work on same feeder fiber or ODN without any extra deployment of fiber. Results revealed that NGPON2 performs better than GPON at every distance from 5 km to 30 km in terms of Q factor and BER. Further analysis of different LP mode profiles in proposed system has been done and it is evident that LP11 mode performs best and LP12 performs worst. Therefore, proposed system is enhanced in performance, cost efficient, uses same ODN, reliable for the future generation networks.

5.2 FUTURE SCOPE

In future, the present work may be extended on the following lines:

1. In this dissertation, backward compatibility of passive optical networks is demonstrated. However, forward compatibility can also be investigated in near future.
2. Investigation of TWDM PON at 1 nm wavelength spacing is considered in the work. Work can also be studies on less channel spacings.
3. Non return to zero modulation format is considered in the proposed work. More highly efficient modulation can be incorporated in the system in near future.
4. Performance of diverse linearly polarized modes is studied in this work. In future, work can be extends for even modes, odd mode for their performance evaluations.

REFERENCES

1. Tomoaki O. *et al. Optical Synchronous CDMA, Encyclopaedia of Telecommunications,* Editor: John Proakis, Wiley, 2002.
2. Banerjee A., *et al.* (2005). Wavelength Division Multiplexed Passive Optical Network (WDM-PON) Technologies for Broadband Access: A Review, *Journal of Optical Networking*, 4(11), pp. 797-758.
3. Yadav R. (2012). Passive Optical Network (PON) based Converged Access Network, *IEEE/OSA Journal of Optical Communications and Networking*, 4(11), pp. B124-B130.
4. Asthana R. and Singh Y. N.(2004). Protection and Restoration in Optical Networks, *IEEE Journal of Research*, 50(5), pp. 319-329.
5. Cedric F. L., *Passive Optical Networks-Principles and Practice,* Editor: Cedric Lam, Elsevier Science and Technology, 2007.
6. Ahsan M. S. *et al.* (2011). Migration to the Next Generation Optical Access Network, *Journal of Networks*, 6(1), pp. 18-25.
7. S. M. Faizan*et al.* (2015). Reach Extendibility of Passive Optical Network Technologies, *Optical Switching and Networking*, 18(3), pp. 211-221.
8. Fok M. P. *et al.* (2011). Optical Layer Security in Fiber-Optic Networks, *IEEE Transactions on Information Forensics and Security*, 6(3), pp. 725 – 736.
9. Pesavento G., Kuo J. C. and Koyama T.(2002). IEEE Access Standards, 802.3ah GE- PON Status, *ITU-T Workshop IP/Optical*, pp. 1-15.
10. ITU-T (2008). Gigabit-capable Passive Optical Networks (GPON): General Characteristics, *ITU-T Recommendation G.984.1*.
11. Lee C. H., Sorin W. V. and Kim B. Y. (2006). Fiber To The Home using a PON Infrastructure, *Journal Of Lightwave Technology*, 24(12), pp. 4568-4583.
12. Shaddad R. Q. *et al.* (2014). A Survey on Access Technologies for Broadband Optical and Wireless Networks, *Journal of Network and Computer Applications*, 41(2), pp. 459–472.
13. Nirmalathas A. *et al.* (2010). Digitized Radio-Over-Fiber Technologies for Converged Optical Wireless Access Network, *Journal of Lightwave Technology*, 20(16), pp. 2366-2375.
14. Berdague S., Facq P. (1982). Mode division multiplexing in optical fibers, *Applied Optic,* 21(11)*,* pp. 1950-1955.

15. Pillay S. *et al.* (2013). Weakly Guiding Fibers and LP Modes in Circular and Elliptical Waveguides, *Journal of Electromagnetic Analysis and Applications*, 5 (8), pp. 333-335.

16. S Anis M. I., Qureshi M. S., Zafar S. (2017). Demonstration of TWDM-PON Backward Compatibility with Conventional GPON, *Wireless personal communication, Springer,* 95 (2), pp. 581-592.

17. Xia C. *et al.* (2015). Time-division-multiplexed few mode passive optical network, *Optics Express,* 23 (2), pp. 1151-1158.

18. Goyal R., Kaler R. S. and Kamal T. S. (2017). A Cost Effective Bidirectional Hybrid Passive Optical Network using Common Carrier for All Optical Network Units (CCAONUs) Technique with Mitigation of Non-Linearity Impact, *Optik- International Journal for Light and Electron Optics*, 130(2), pp.644-649.

19. Kaur A., Sheetal A. and Miglani R. (2017). Imapct of Optical Modulation Formats on 10G/2.5G Asymmetric XG-PON System, *Optik- International Journal for Light and Electron Optics*, 59671, pp. 36–42.

20. Kaur A., Kaur B. and Singh K.(2017). Design and Performance Analysis of Bidirectional TWDM-PON employing QAM-OFDM for Downstream and Re-modulation for Upstream, *Optik- International Journal for Light and Electron Optics*, 134, pp. 287-294.

21. Houtsma V. and Veen D. (2017). A Study of Options for High Speed TDM-PON beyond 10G, *Journal of Lightwave Technology*, 35(4), pp. 1059–1066.

22. Abbas H. S. and Gregory M. A. (2016). The Next Generation of Passive Optical Networks: A review, *Journal of Network and Computer Applications*, 67, pp. 53-57.

23. Liu X. and Effenberger F. (2016). Emerging Optical Access Network Technologies for 5G Wireless, *Journal of Optical Communications and Networking*, 8(12), pp. B70-B79.

24. Andrade M. D. *et al.* (2015). Optimization of Long-reach TDM/WDM Passive Optical Networks, *Optical Switching and Networking*, 16, pp. 36–45.

25. Bindhaiq S., *et al.* (2015). Recent Development on Time and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) for Next-Generation Passive Optical Network Stage 2 (NG-PON2), *Optical Switching and Networking*, 15, pp. 53–66.

26. Shaddad R. Q. *et al.* (2014). Fiber-Wireless (FiWi) Access Network: Performance Evaluation and Scalability Analysis of the Physical Layer, Optik, 125, pp. 5334-5338.

27. Emsia A. *et al.* (2014). WDM–TDM NG-PON Power Budget Extension by Utilizing SOA in the Remote Node, *IEEE Photonics Journal*, 6(2), pp. 1-10.

28. Pandey G. and Goel A. (2014). Performance Analysis of Symmetrical 10 Gbps colorless WDM-PON using Subcarrier Modulated Downstream and Wavelength Converted Upstream through RSOA, *Optik- International Journal for Light and Electron Optics*, 125(17),pp. 4951-4954.

29. Bi M. *et al.* (2014). Power Budget Improved Symmetric 40-Gb/s Long Reach Stacked WDM-OFDM-PON System Based on Single Tunable Optical Filter, *IEEE Photonics Journal*, 6(2), pp. 1-8.

30. Jaumard B. and Chowdhury R. (2013). An Efficient Optimization Scheme for WDM/TDM PON Network Planning, *Computer Communications*, 36(14), pp. 1539–1551.

31. Dixit A. *et al.* (2013). Flexible TDMA/WDMA Passive Optical Network: Energy Efficient Next-Generation Optical Access Solution, *Optical Switching and Networking*, 10(4), pp. 491–506.

32. Chow C. W. and Yeh C. H. (2013). Using Downstream DPSK and Upstream Wavelength Shifted ASK for Rayleigh Backscattering Mitigation in TDM-PON to WDM-PON Migration Scheme, *IEEE Photonics Journal*, 5(2), pp. 7900407-7900407.

33. Chien Y. *et al.*(2011). Ring-Based WDM-PON with Suppression of Rayleigh Backscattering Interferometric Noise, *OSA, Conference OSA Technical Digest,* Canada

34. Goyal R. and Kaler R. S. (2012). A Novel Architecture of Hybrid (WDM TDM) Passive Optical Networks with suitable Modulation Format, *Optical Fiber Technology*, 18(6), pp. 518-522.

35. Zhang R. and Ma J. (2017). Full-duplex Hybrid PON/ROF Link with 10-Gbit/s 4-QAM Signal for Alternative Wired and 40-GHz Band Wireless Access based on Optical Frequency Multiplication, *Optik-International Journal for Light and Electron Optics*, 138, pp. 55–63.

36. Novak D., *et al.* (2016). Radio-Over-Fiber Technologies for Emerging Wireless Systems, *IEEE Journal of Quantum Electronics*, 52(1), pp. 1-12.

37. Sarup V. and Gupta A. (2015). A Study of various Trends and Enabling Technologies in Radio Over Fiber (ROF) Systems, *Optik- International Journal for Light and Electron Optics*, 126(20), pp. 2606-2611.

38. Elmagzoub M.A. *et al.* (2015). New ROF-PON Architecture using Polarization Multiplexed Wireless MIMO Signals for NG-PON, *Optics Communications*, 344, pp. 55–64.

39. Cheng G. *et al*. (2014). A Novel Full-Duplex Radio-Over-Fiber System based on Dual Octupling-frequency for 82GHz W-band Radio Frequency and Wavelength Reuse for Uplink Connection, *Optik- International Journal for Light and Electron Optics*, 125(15) , pp. 4072-4076.

40. Aldhaibani A.O., Idrus S. M. and Zulkifli N. (2013). 2.5 Gb/s Hybrid WDM/TDM PON using Radio Over Fiber Technique, *Optik- International Journal for Light and Electron Optics*, 124(18), pp. 3678-3681.

41. Aldaya I., *et al.* (2013). A Survey of Key-enabling Components for Remote Millimetric Wave Generation in Radio Over Fiber Networks, *Optics & Laser Technology*, 49, pp. 213–226.

42. Zhu M., *et al.* (2013). Radio-Over-Fiber Access Architecture for Integrated Broadband Wireless Services, *Journal of Lightwave Technology*, 31(23), pp. 3614 – 3620.

43. Mitatha S., Putthacharoena R. and Yupapin P. P. (2012). THz Frequency Bands Generation for Radio-over-Fiber systems, *Optik- International Journal for Light and Electron Optics*, 123(11), pp. 974-977.

44. Hsueh Y. T., *et al.* (2011). A Novel Lightwave Centralized Bidirectional Hybrid Access Network: Seamless Integration of ROF with WDM-OFDM-PON, *IEEE Photonics Technology Letters*, 23(15), pp. 1085-1087.

45. Kim A., Joo Y. H. and Yungsoo K. (2004). 60GHz Wireless Communication Systems with Radio-over-Fiber Links for Indoor Wireless LANs, *IEEE Transactions on Consumer Electronics*, 50(2), pp. 517–520.

46. Gill H. S., Gill S. S. and Bhatia K. S. (2017). A Novel Chaos-Based Encryption Approach for Future-Generation Passive Optical Networks Using SHA-2, *OSA*, 9(12), pp. 1184-1190.

47. Perez G. *et al.* (2006). Efficient modulation formats for high bit-rate fiber transmission, *Acta Universitaria*, 16(2), pp. 17–26.

48. Parol, P., & Pawloski, M. (2013). Towards networks of the future: SDN paradigm introduction to PON networking for business applications, *In Proceedings of the 2013 federated conference on computer*, pp. 829–836.
49. Sultan, D. M. S., & Arefin, M. T. (2011). GPON, the ultimate pertinent of next generation triple-play bandwidth resolution, *Journal of Telecommunications and Information Technology*, 2, pp. 53–60.
50. Singh, S., Jaiswal, A. K., & Kumar, M. (2012). Transmission of voice, video and data in fiber-to-the home (FTTH) networks using OFDM, *IJARCSSE*, 2(5), pp. 41–45.
51. Taheri, M., & Ansari, N. (2013). A feasible solution to provide cloud computing over optical networks, *IEEE Network*, 27(6), pp. 31–35.
52. Srinath, S. (2014). Performance analysis of 2.5 Gbps GPON, *IJAREEIE*, 3(6), pp. 10148–10155.
53. Milanovic, S. (2014). Case study for a GPON deployment in the enterprise environment, Journal of Networks, 9(1), pp. 42–47.
54. Santos-Boada, G., & Domingo-Pascual, J. (2006). Quality of service in multi operator GPON access networks with triple-play services, *World Academy of Science, Engineering and Technology,* 18.
55. Bakarman, H. A., Shaari, S., & Ismail, M. (2010). Simulation of 1.25 Gb/s downstream transmission performance of GPON-FTTx, *In International conference on photonics 2010*, pp. 1–5.
56. Orphanoudakis, T., *et al.* (2009). Performance evaluation of GPON vs EPON for multi-service access, *International Journal of Communication Systems*, 22(2), pp. 187–202.
57. Sumanpreet, M., & Dewra, S. (2014). A review on Gigabit Passive Optical Network (GPON), *International Journal of Advanced Research in Computer and Communication Engineering*, 3(3), pp. 5844–5848.
58. Winzer, P. J., & Essiambre, R.-J. (2006). Advanced optical modulation formats, *Proceedings of the IEEE*, 94(5), pp. 952–985.
59. Cheng, N., *et al.* (2013). World‘s first demonstration of pluggable optical transceiver modules for flexible TWDM PONs, *In Proceedings of ECOC*.
60. Luo Y. *et al.* (2013). Time-and wavelength division multiplexed passive optical network (TWDM-PON) for next-generation PON stage 2 (NGPON), *Journal of Lightwave Technology*, 31(4), pp. 587–593.

61. Yi L. (2013). Symmetric 40-Gb/s TWDM-PON with 39-dB power budget, *IEEE Photonics Technology Letters*, 25(7), pp. 644–647.

62. Eslam A. *et al.* (2013). Coherent Long Reach OIDMA-PONs Enabled By Electronic Dispersion Compensation, *Asia Communications and Photonics Conference 2013, Optical society of America,* China.

63. Caballero D. R. V. *et al.* (2016). Experimental Demonstration of SCM-PON Monitoring with Baseband Embedded OTDR, *Fiber and Integrated Optics,* 36 (1), pp. 59-67.

64. Saliou F. *et al.* (2009). Reach Extension Strategies for Passive Optical Networks, *Journal of Optical Communications and Networking,* 1 (4), pp. C51-C60.

LIST OF PUBLICATIONS BY THE CANDIDATE