

Performance Analysis of Hybrid Passive Optical Networks

A Thesis

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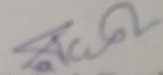
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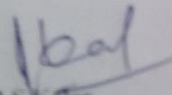
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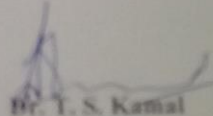
I, Rakesh Goyal hereby certify that the work which is being presented in this thesis entitled "Performance Analysis of Hybrid Passive Optical Networks" in partial fulfillment of requirements for the award of degree of the Doctor of Philosophy in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried under the supervisions of Dr. R. S. Kaler and Dr. T. S. Kamal. The matter presented in this thesis has not been submitted in any other University/ Institute for the award of any degree or diploma.

Date: 19th Nov, 2014


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Abstract

The rapid augmentation in the access networks demands huge bandwidth to provide voice, data and video (triple play) services for residential and corporate subscribers. Due to the higher bandwidth requirement, optical broadband access networks are the most promising solution for the demand of high channel capacity at longer transmission distance. The researchers are giving more focus on the designing and implementation of innovative access system architecture, sustaining huge data at high speed with larger bandwidth for the next generation demands. Passive Optical Networks (PONs) appealed to provide a lucrative, highly flexible and scalable network for all the end subscribers. One aspect of achieving higher data rates over fiber to fulfill the large bandwidth demand is multiplexing techniques. On the basis of multiplexing techniques, PONs can be divided into two main schemes viz. Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM) schemes. In recent times, researchers are aiming at the concepts of hybrid (WDM/ TDM) PON. This thesis deals with the performance evaluation of hybrid PON systems by designing new architectures, finding out suitable amplifier, improving the overall performance by mitigating & analyzing the crosstalk and implementing different topologies with tracking several system level challenges while acknowledging the limitations of existing networks.

In order to achieve these objectives, it is utmost important to design, characterize and investigate hybrid PON for high capacity access systems. Firstly, we have proposed various architectures of hybrid PONs and analyzed the performance and feasibility of these architectures. In the first architecture, a hybrid PON using triple play services is simulated for 128 Optical Network Units (ONUs) for suitability of various data formats. Further, a bidirectional hybrid PON using circulator has been investigated for different data rates i.e. 1.25, 2.5, 5 and 10 Gbps. The next architecture is designed for Mixed Line Rates (MLRs) for 10/ 20/ 40 Gb/s to meet the requirement of high volume of heterogenic traffic. The investigation is focused on uniform channel spacing and mixed channel spacing for MLRs. 50 GHz spacing is kept in case of uniform spacing and 20, 50 & 100 GHz spacing for 10, 20 & 40 Gbps data rates is given in case of mixed spacing respectively. It is found that mixed channel spacing for MLRs shows better results than conventional uniform channel spacing. Further, the network is constructed based on a novel technique i.e. cost effective using common carrier for all optical network units technique. A carrier is engendered at the central

office (CO) and remodulated for upstream transmission at the subscriber end making ONU very simple and cost effective. So, there is no requirement of laser sources for generation of carrier at the ONU end. In this way, by using the extra carrier at Optical Line Terminal (OLT), we have reduced the laser sources equal to the number of ONUs.

Further, we have proposed different aggressive schemes to reduce the energy consumption viz. no buffer, with buffer, reduced buffer and reduced buffer with small packet. The reduced buffer with small packet scheme has shown a reduction of more than 35% of total leakage power at the central office with the compromise of delay in packets receiving. Bidirectional hybrid PONs for Raman, Semiconductor Optical Amplifier (SOA) and Erbium Doped Fiber Amplifiers (EDFA) using polarization modulation technique in swing with Quadrature Amplitude Modulation (QAM) at 5 Gbps data rate has also been proposed. Further, the system is enhanced to 10 Gbps data rate with 128 ONUs using polarization modulation with 16-QAM to utilize the maximum bandwidth. It has been observed that EDFA amplifier shows better performance than SOA and Raman.

Then, a bidirectional hybrid PON for the various fiber nonlinearities like Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), Four Wave Mixing (FWM) and Cross Phase Modulation (XPM) is analyzed theoretically. The proposed system is very simple, flexible, expandable and cost effective. All kind of distortions at the same frequency, phase and power are included into the same signal. The resultant signal is sent to a threshold device where a threshold level is defined on the basis of the centre frequency of these distortions. The output of the threshold device is free from distortions. Different wavelengths for downstream and upstream i.e. 1550 nm and 1300 nm are also used to mitigate the crosstalk effect of same wavelength in the fiber respectively.

Further, we have investigated the network for 1024 number of users with hybrid (ring-tree) topology form using Add Drop Multiplexers. A cost effective fault protection scheme is also proposed for hybrid passive optical network using ring topology. This scheme provides the full fault protection to PON without installing the extra standby fiber in the ring network.

Therefore, this investigation establishes to design, characterize and investigate hybrid PON as high capacity access systems resulting in the revolutionary growth of internet traffic for terrestrial fiber backbone networks.

List of Publications

1. Rakesh Goyal, R.S. Kaler, “A novel architecture of hybrid (WDM/ TDM) passive optical networks with suitable modulation format,” *Optical Fiber Technology*, vol. 18, no. 6, pp. 518–522, December 2012.
2. Rakesh Goyal, R.S. Kaler, “Performance investigation of bidirectional Hybrid (wavelength division multiplexing/ time division multiplexing) passive optical network,” *Optoelectronics and Advanced Materials – Rapid Communications*, vol. 8, no. 7-8, pp. 663-667, August 2014.
3. Rakesh Goyal, R.S. Kaler, “Investigation on polarization dependent bidirectional hybrid (WDM/ TDM) utilizing QAM modulation with different amplifiers,” *Optoelectronics and Advanced Materials – Rapid Communications*, vol. 8, no. 7-8, pp. 631-634, August 2014.

Acknowledgment

गुरुर्ब्रह्मा गुरुर्विष्णुः गुरुर्देवो महेश्वरः।
गुरुः साक्षात् परब्रह्म तस्मै श्रीगुरुवे नमः ॥

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Finally, words are not adequate to express my gratitude to my brother, **Mr. Man Mohan** & his wife, **Ms. Deepti** and my sisters, **Ms. Kiran, Ms. Sunita & Ms. Shanti** and *Jija Ji*, **Mr. Sanjay Jain, Mr. Jai Pal Garg & Mr. Sandeep Garg** for the patience, support and active assistance in many ways.

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(Rakesh Goyal)

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List of Acronyms

AM	Amplitude Modulation
AON	Active Optical Network
ASE	Amplified Spontaneous Emission
ASK	Amplitude Shift Keying
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BFP	Backup Fibers Protection
BMS	Burst Mode Sensitivity
BPON	Broadband PON
BS	Brillouin Scattering
CCAONUs	Common Carrier for All Optical Network Units
CNR	Carrier to Noise Ratio
CO	Central Office
CW	Continuous Wave
DCF	Dispersion Compensated Fiber
Demux	Demultiplexer
DFB	Distributed Feed Back
DQPSK	Differential Quadrature Phase Shift Keying
DRFA	Distribute Raman Fiber Amplifier
DS	Dispersion Shifted
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EML	External Modulated Laser
EPON	Ethernet Passive Optical Network
ESG	Electrical Signal Generator
FBG	Fiber Bragg Grating
FFT	Finite Fourier Transform
FP	Fabry–Perot
FTTB	Fiber To The Building
FTTC	Fiber To The Curb
FTTH	Fiber To The Home
GEPON	Gigabit Ethernet PON
GPON	Gigabit-capable Passive Optical Network
GSM	Global System for Mobile Communications
HPON	Hybrid Passive Optical Network
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programming
IRZ	Inverse Return-to-Zero
ITU	International Telecommunication Union
LASER	Light Amplification through Stimulated Emission of Radiation

LED	Light Emitting Diode
Mux	Multiplexer
MWLS	Multi Wavelength Light Sources
MZ	Mach-Zehnder
MZM	Mach-Zehnder Modulator
NB	No Buffer
NLSE	Non Linear Schrodinger Equation
NRZ	Non Return to Zero
OADM	Optical Add Drop Multiplexer
OCDMA	Optical Code Division Multiplexing Access
ODEs	Ordinary Differentially Equations
ODN	Optical Distribution Networks
O-E-O	Optical-Electrical-Optical
OFDM	Orthogonal Frequency Division Multiplexing
OHL	Optical Hardware Limiter
OLT	Optical Line Terminal
ONT	Optical Network Terminal
ONU	Optical Network Unit
OOK	On-Off Keying
P2MP	Point To Multipoint
P2P	Point To Point
PBC	Polarization Beam Combiner
PBS	Polarization Beam Splitter
PON	Passive Optical Networks
PRBS	Pseudo Random Bit Sequence
PSK	Phase Shift Keying
PSSL	Pre-spectrum Sliced Seed Lights
RB	Reduced Buffer
RBSP	Reduced Buffer with Small Packet
RF SCM	Radio Frequency Sub-Carrier Multiplexed
RN	Remote Node
ROF	Radio Over Fiber
RS	Rayleigh Scattering
RSOA	Reflective Semiconductor Optical Amplifier
RZ	Return to Zero
SARDANA	Scalable Advanced Ring based passive Dense Access Network Architecture
SCM	Sub Carrier Modulation
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
SRLG	Shared-Risk Link Group

TDM	Time Division Multiplexing
TOF	Tunable Optical Filter
TSOA	Travelling wave Semiconductor Optical Amplifier
VCSEL	Vertical Cavity Surface Emitting Diodes
VoIP	Voice over IP
WB	With Buffer
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
Wifi	Wireless Fidelity
WiMAX	Wireless Interoperability for Microwave Access
WSS	Wavelength Selective Switch
XG	Next Generation
XPM	Cross Phase Modulation

Chapter 1

Introduction

The communication is the prime necessity for mankind throughout its history. To communicate at longer distances, a number of ways were used like sending of message through pigeons and smoke signals. As the technology improved, the information is being transmitted and received easily. The copper wires, co-axial cables are used to communicate for a long period of time. There is major evolutionary change in the communication system with the invention of optical fiber. Now-a-days, fiber optical communication has become one of the most essential medium for high data rate transmission up to long distances. The major advantage of the optical communication is the enormous bandwidth availability provided by the fiber [1]. In the early days, the optical fiber could not be used for commercial applications because it had a very high attenuation up to 1000 dB/km. But currently various optical fibers are available with low losses (0.2 dB/km) which can be efficiently utilized in various multi-terabit and bandwidth efficient applications. Optical networks have knocked the doors of communication world with their great ability to sustain robust conditions, support for asynchronous data traffic and much better response to multiple access techniques. The design and characterization of optical broadband access networks is the main focus for proving themselves as the solution for the next generation networks [2]. Passive Optical Networks (PONs) dominate among other access networks for providing high speed data to longer distance cheaply to the end subscribers [3]. Various networks using different multiplexing techniques like Optical Code Division Multiplexing Access (OCDMA), Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM) schemes are proposed and discussed. Now-a-days, the researchers are endeavoring at the concepts of combination of two or more techniques e.g. hybrid (WDM/ TDM) PON [4].

To achieve the desired data at high speed, these networks should be capable of utilizing the bandwidth and should have the capability to handle efficiently all the functions such as wavelength multiplexing, de-multiplexing, adding & dropping wavelength, splitting, combining and amplification etc. [5]. Different architectures have been proposed by the researchers for installing the fiber from Central Office (CO) to the subscriber's end to provide triple play services. The main drawback to employ these networks is the high

installation cost of the optical fiber and other components [6]. Various technologies are invented or suggested to overcome this problem. Some networks based on these technologies are listed here.

1.1 Fiber Access Networks

Optical fibers communication system is becoming most popular due to very low noise and large bandwidth properties. In current times, the major focus in optical networks is to reduce the cost of the optical network system. The fiber is very expensive as compared to copper but due to very low maintenance requirement and providing larger capacity, the fiber is more economical as compared to all other physical media [5]. Also, new technologies and components are designed to decrease the overall cost of system. The advantages of small weight, size and immunity to electromagnetic interference make fiber a better substitute to copper in new generation networks [7]. The fiber technology is implemented in existing ducted systems in metro cities. In these access networks, the optical fiber is used to replace all or part of the existing copper cable or coaxial cable. The fiber can be installed to subscriber's home, building/ office or an in-between office or curb. On account of fiber deployment, the networks are generalized as FTTx, where x is replaced by the specific network. These FTTx scenarios can be developed in several configurations such as home (FTTH), Building (FTTB) and Curb (FTTC) [8].

1.1.1 Fiber To The Curb

A high capacity fiber is installed between CO to the curb so that it can provide the services to large area in this architecture. The media between subscriber location and curb is copper and there is need to choose an appropriate location for the terminal where the distribution cost, back feeding, additional cost can be reduced. The main advantage of the FTTC is that it cuts down the installation cost of multiple fiber to all the subscribers. The drawback of this architecture is the requirement of larger and suitable space and availability of power and other facility to functionalize the curb smoothly [7].

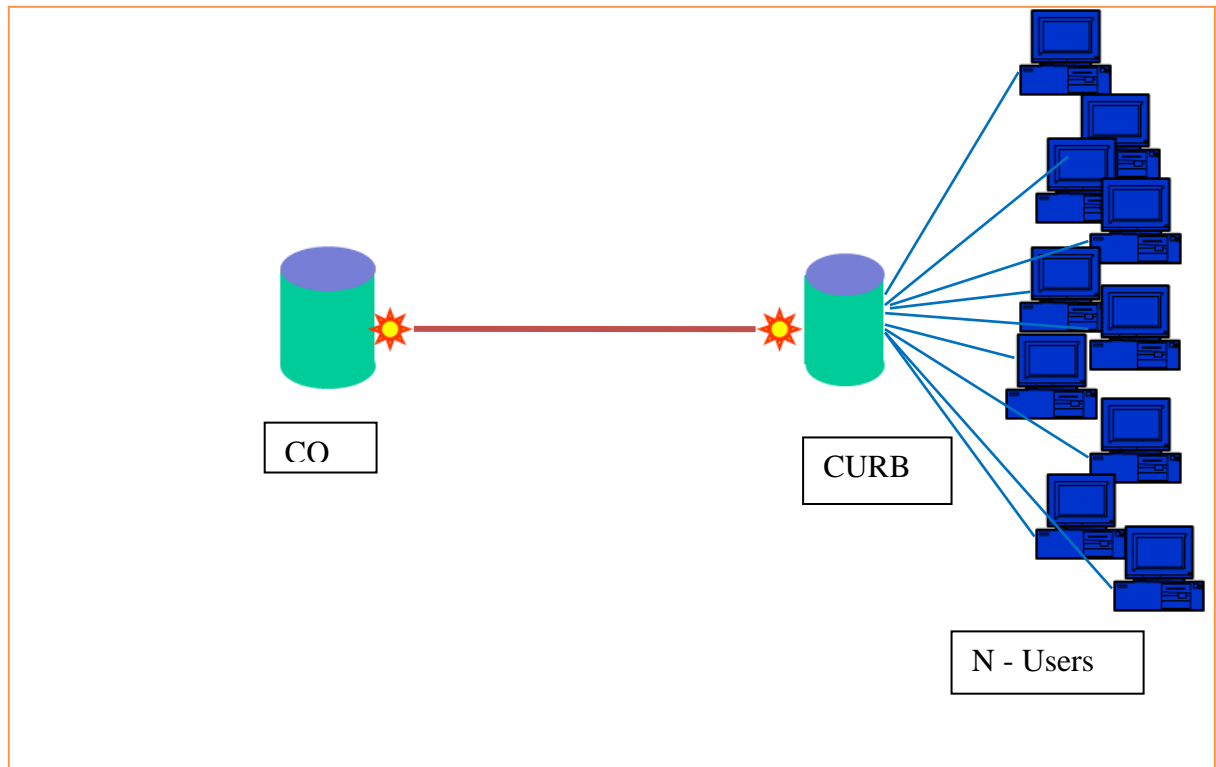


Figure 1.1: FTTC

A fiber to the curb network system is shown in the figure 1.1. The main advantage of this network is that it requires of only two optical transceivers. But there is a small bandwidth available from transceiver to end users due to the use of copper wires at the subscriber's end and the complex converter used at the curb.

1.1.2 Fiber To The Home

The FTTH architecture is shown in the figure 1.2. In this configuration, an optical fiber is installed between CO to the office/ home. It gives the most powerful system which provides the largest bandwidth to the subscriber [2]. It consists of $2N$ transceivers located at the central office and at the end users side. This configuration requires more amount of fiber. The number of components in this network can be reduced by using active or passive optical switches.

A fiber to the home network using active switch is shown in figure 1.3. An active switch located at the basement of the building will transmit the optical signal to the end users. Thus, it saves the space at the central office and single fiber can be used from central office to the curb or basement. But, there will be need of $2N$ optical transceivers at the curb and end users side and 2 optical transceivers at the central office and curb. So, there is requirement of $2N + 2$ optical transceivers.

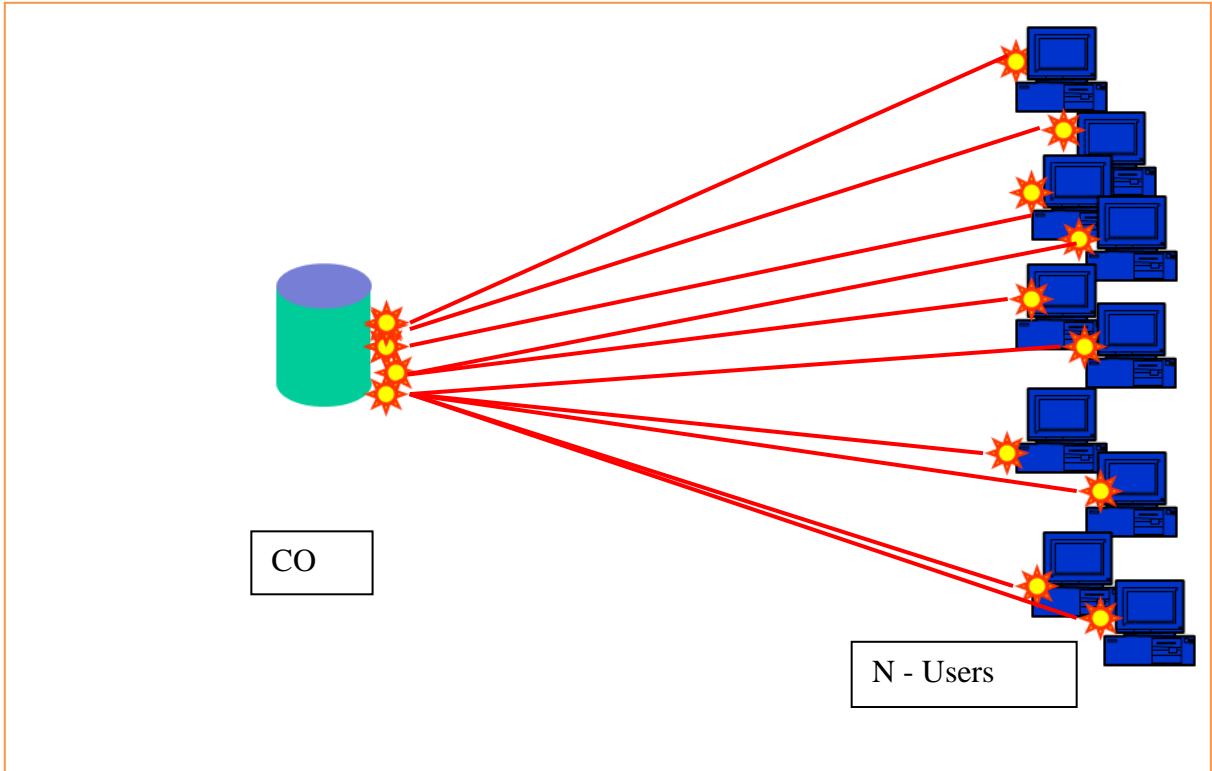


Figure 1.2: FTTH

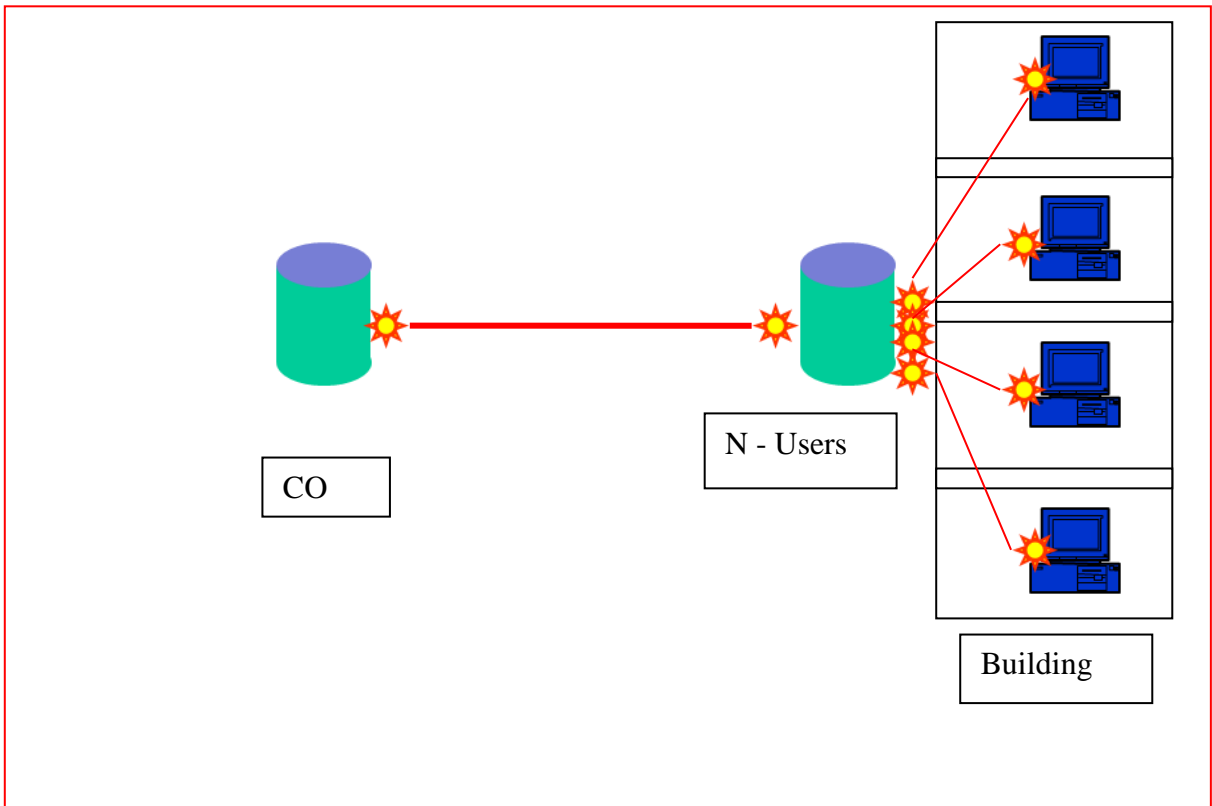


Figure 1.3: Fiber to the home network using active optical switch

1.1.3 Passive Optical Networks (PON)

Another alternative to reduce the number of optical transceivers is to use passive optical networks. In these networks, the optical signal is switched through passive splitters. Passive splitters do not require external power source for their operation [3]. Also, these networks require $N+1$ optical transceivers and there is no need of electro-optical conversion. A passive optical network for n numbers of users is shown in the figure 1.4. This technology ensures to support the upcoming interactive multimedia services.

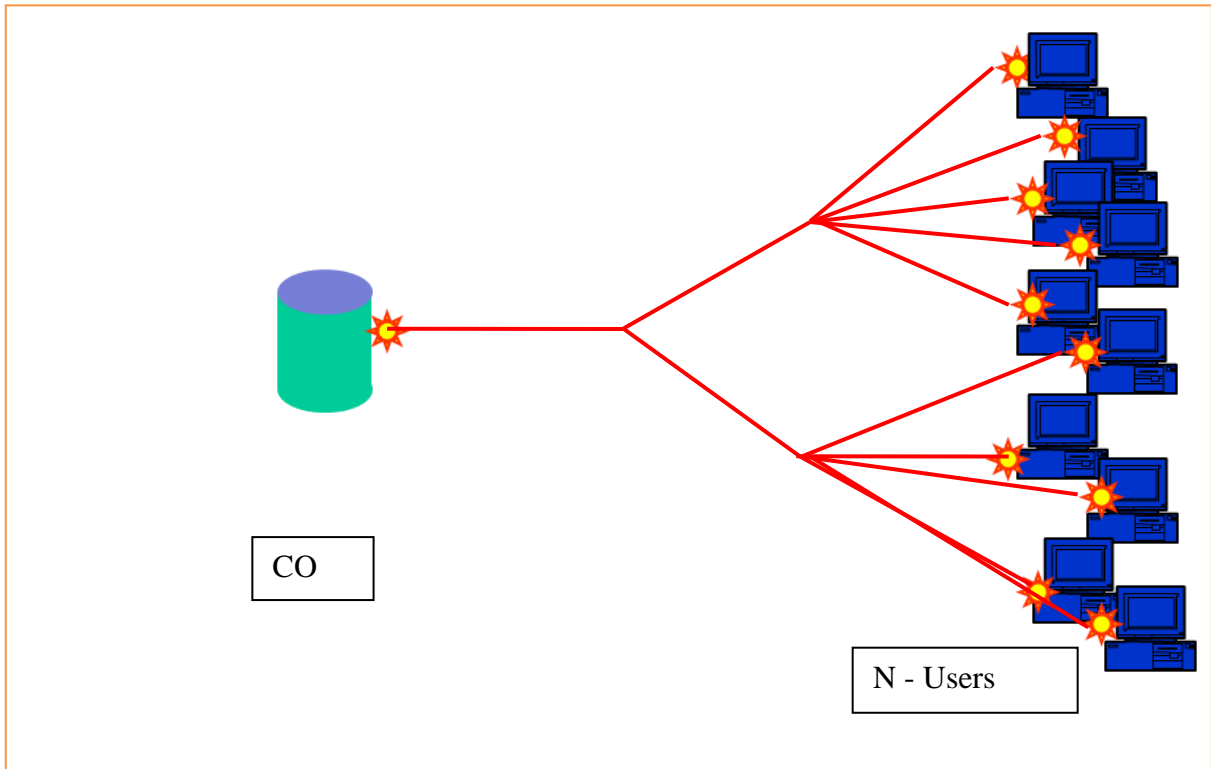


Figure 1.4: Passive optical networks

PONs topologies are classified as Point To Point (P2P) and Point To Multipoint (P2MP) topologies. In P2P topology, there is direct fiber link between CO and end user, which is very expensive. To reduce the installation costs, P2MP architecture is used where different users transmit/ receive data using single fiber link. Various standards have been recommended for passive optical networks. The main PON technologies are standardized as the Broadband PON (BPON) ITU-T G.983, Gigabit PON (GPON) ITU-T G 984 by International Telecommunication Union (ITU) and Ethernet Passive Optical Network (EPON) IEEE 802.3 by IEEE (Institute of Electrical and Electronics Engineers). Different multiplexing techniques can be used to implement these networks. In WDM PON, the available bandwidth is divided into different wavelengths and a single wavelength is assigned to each user. The users can transmit and/ or receive the data using the assigned

wavelength at any time. In TDM PON, the full bandwidth is available to each user for different time slots. In Hybrid (WDM/ TDM) PON system, the advantages of both multiplexing techniques are provided to the end users [4]. On these basics, different types of PON are specified. Different standards of PON systems are described below:

1.1.3.1 BPON (Broadband PON): BPON system is the first Passive optical network standard. This system is based upon Asynchronous Transfer Mode (ATM) protocol. Initially, the name was ATM PON and used primarily for business applications. The standard set by International Telecom Union for BPON is ITUG.983. BPON data packet cell size contains 53 bytes of data. It has 1.2 Gbps data rate for downstream and 622 Mbps for upstream [9].

1.1.3.2 EPON or GEAPON (Ethernet PON or Gigabit Ethernet PON): The standard set for EPON is an IEEE standard 802.3ah which comes under the category of IEEE 802.3 standard. The purpose of EPON is to implement Ethernet technology in the PON systems to enhance the capabilities of the network with less number of components/equipments at very low operation & maintenance cost [10]. EPON data packet cell size contains 1518 bytes of data. It supports P2MP subscriber access network topology.

1.1.3.3 GPON (Gigabit-capable Passive Optical Network): It is standardized by ITU as ITUG.984. GPON has variable data packet cell size from 53 bytes to 1518 bytes. The data rate of GPON is configurable from 1.2 Gbps to 2.5 Gbps for downstream and for upstream different data rates of 155 Mbps, 622 Mbps, 1.25 Gbps or 2.5 Gbps can be used [11]. It uses ATM, Ethernet and TDM protocol. GPON offers more facilities but it is more complex. The next-generation GPON standard, which is classified as XG-PON1, has been released in 2010. A number of options have been considered for next generation broadband access standard (NG-PON2).

1.1.3.4 10 G-EPON (10 Gigabit Ethernet PON): 10 G-EPON is standardized by IEEE. In this configuration, the data rate is kept as 1 and 10 Gbps for upstream and downstream respectively. It is also made companionable with EPON. The main characteristic of 10 G-EPON is the utilization of same wavelength for downstream and upstream. These architectures are based upon TDMA technology. The various applications of GEAPON are broadband services for internet, triple play services, online media streaming and gaming etc. Table 1 shows the various characteristics of different PON standards.

Table 1.1: Characteristics of different PON standards

Parameters	Broadband PON	Ethernet PON	Gigabit PON
Standardized by	ITU-T G.983	IEEE 803.2ah	ITU-T G.984
Data Packet Cell Size	53 bytes (48 payload and 5 overhead)	1518 bytes	Configurable from 53 bytes up to 1518 bytes
Maximum Data Rate	Downstream: 1.2 Gbps Upstream: 622 Mbps	1.25Gbps (symmetric)	Downstream: 1.2 Gbps - 2.5Gbps Upstream: 155 Mbps, 622 Mbps, 1.25Gbps or 2.5 Gbps
Wavelength	Downstream: 1480nm to 1500nm Upstream: 1260nm to 1360nm	Downstream: 1550nm Upstream: 1310nm	Downstream: 1480nm to 1500nm Upstream: 1260nm to 1360nm
Traffic Modes	Asynchronous Transfer Mode	Ethernet	Asynchronous Transfer Mode, Ethernet, TDM
Voice	TDM	VoIP or TDM	Native TDM
Max. PON splits	32	16	64

1.1.3.5 TDM PON

TDM PON works on the time multiplexing protocol and it is the most common PON architecture. In this configuration, the users can transmit and / or receive their data as per assigned time slots. The whole bandwidth is available to all the users. The circuits use power splitters for synchronization. ONUs recognize their data through the specific packet headers attached with the signal. A TDM PON architecture using power splitter is shown in the Figure 1.5.

Advantages of TDM PON:

- No need to control the transmitter power.
- Repeater job is simplified.
- Data transmission is not continuous so it results in less power consumption.

TDM-PON has following drawbacks [12]:-

- Bandwidth sharing: The bandwidth per ONU is available for limited time.
- Limited transmission range due to the power split losses associated with the optical splitter.

- Security issue: It requires algorithms to secure the information in downstream signals because the downstream information is shared by each ONU.
- TDM-PON has complicated bandwidth allocation protocol.

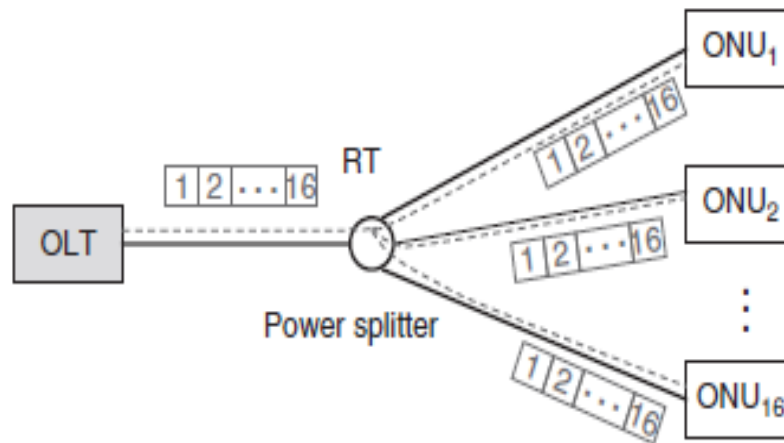


Figure 1.5: TDM PON Architecture

1.1.3.6 WDM PON: In the last two decades, the traffic demand in the Internet is increased rapidly. The rate of this escalation is expected more in the future. So, there is need to improve the existing system to meet the future requirements. The capacity of the networks can be increased by assigning the different wavelengths to the multiple users which share a single fiber. Also, the cost of installation will be very less due to reduction in cost per customer. This is the main reason that WDM will remain a promising solution to fulfill the requirement of more bandwidth in future.

WDM PON is the ultimate solution for fast, efficient and secure bandwidth allocation for passive optical networks. Various wavelengths add or drop devices are required to perform the WDM task over the same fiber [13]. A WDM PON architecture using WDM coupler is shown in the Figure 1.6.

Advantages of WDM

- Simplicity
- Absence of Synchronization

Disadvantages of WDM

- Lack of flexibility
- Lack of capacity
- Requirement of costly infrastructure

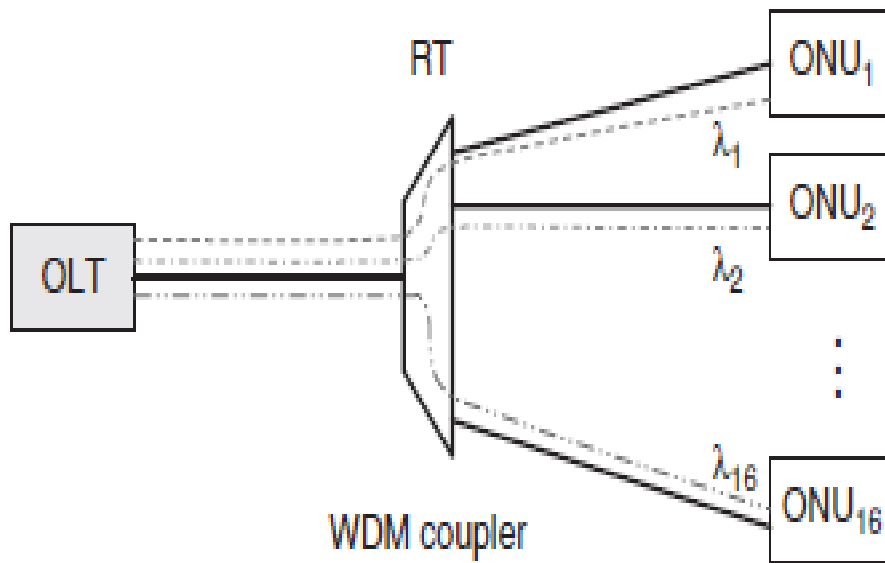


Figure 1.6: WDM PON Architecture

1.1.3.7 WDM/ TDM or Hybrid PON

Hybrid (WDM/ TDM) PON is the system which uses both WDM and TDM techniques. The advantages of both multiplexing techniques are provided to the end users. In figure 1.7, hybrid (WDM/TDM) PON architecture is shown.

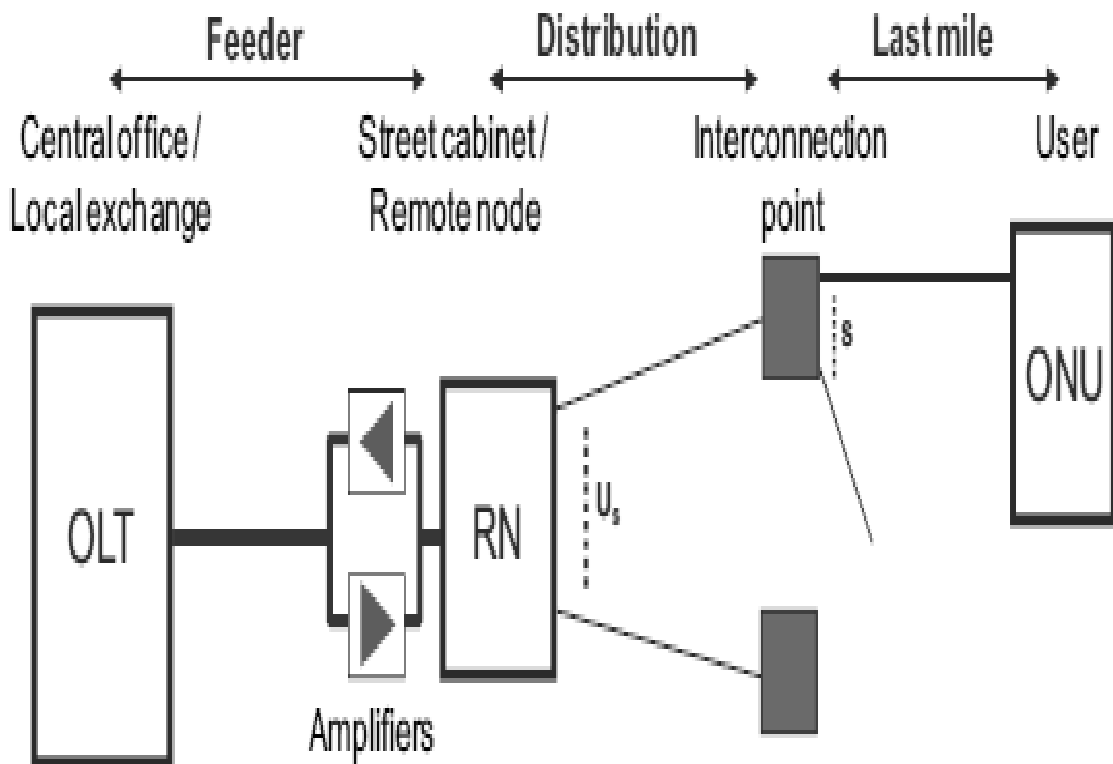


Figure 1.7: Hybrid PON

In this architecture, different wavelengths are used to realize communication between the Central Office (CO) and number of end subscribers. The communication is done in two phases. Firstly, numbers of wavelengths are assigned to the different groups of Optical Network Units (ONUs). Each wavelength will be shared on time basis by several ONUs of the same group. As shown in the figure 1.7, the entire wavelength is divided into number of wavelengths using WDM technique. Each wavelength is shared by a group of number of ONUs using TDM technique and so on.

1.2 Components of PON

1.2.1 Optical Line Terminal: It is located in the CO which offers the services to the number of ONUs. OLT has two float directions viz. uplink and downlink. The transmission from OLT to ONUs is termed as downlink transmission and from ONU to OLT as uplink transmission. The main function of the OLT is to provide smooth communication between network operator and end users through various network interfaces [6].

1.2.2 Optical Network Unit: The ONU is installed within user's premises. It is also termed as Optical Network Terminal (ONT) because it is located in home/ building/ curb etc. This unit provides network access to the users. In other words, this provides an interface to the single or many users. Earlier, ONUs were designed for data reception only but now-a-days, these are capable of transmitting and receiving the data simultaneously.

1.2.3 Splitters and Combiners: These devices are used at the remote node or channel to distribute/ aggregate the signals to and from OLT to the number of ONUs. These devices are available in two types viz. active and passive. Active splitters and combiners which use external power for their operation are used inside the remote node in PON architectures. The passive splitters and combiners do not require external power and can be used in the channel or outside of the remote node. Most commonly used splitters are 1:4, 1:8, 1:16, 1:32 and 1:64 [15].

1.2.4 Arrayed Waveguide Grating: AWGs uses different wavelength for upstream and downstream data transfer [16]. The limitation of AWGs is that the wavelength shifts about 0.01 nm per degree Celsius with variations in temperature which results due to change in the refractive index of silica waveguides. Mostly, AWGs are placed at outdoor

plants without electrical coolers in the passive remote node where temperature varies due to change in environmental changes. Therefore, it is essential to deploy temperature insensitive AWGs. Some efforts have been made to minimize the dependence of channel wavelength on temperature in AWGs [17].

1.2.5 Network Management System: It is a system to handle the overall management of the complete network from central office to each ONU.

- OLT and ONT interface use TDM/TDMA protocol
 - Single and multi mode fiber can be used for upstream & downstream
 - Provides maximum optical split ratio 1:64
 - Provides various fault protection schemes to system failure etc.
- OLT and ONU can be placed at larger distances

1.2.6 Mux/ Demux Devices: Another important component of the PON is Mux/ Demux device. These devices are placed in the remote node to perform multiplexing and demultiplexing through single fiber. Wavelength specific filters must also be placed after the optical splitters. To enhance the capacity of PON system, these Mux/ Demux devices are used with repeaters and/ or optical amplifiers. In repeater, the optical signal is demultiplexed and then regenerated through Optical-Electrical-Optical (O-E-O) conversions. On the other hand, the optical amplifier amplifies the signals without use of O-E-O conversions.

1.2.7 Optical Amplifiers: With the use of optical amplifiers, the capacity of PON systems can be increased drastically. Large gain bandwidth property of optical amplifiers has enabled them to enlarge the number of ONUs by broadcasting many parallel channels placed as wavelength grid in single fiber. Moreover, the low noise figure property of the amplifiers has omitted the need of costly periodic electro-optic regeneration. Also, an optical amplifier can simultaneously amplify more than hundred of 10 Gbps WDM channels, corresponding to 1 Tbps worth of traffic, without O-E-O conversions or any use of high-speed electronics.

Erbium Doped Fiber Amplifier (EDFA), Semiconductor Optical Amplifier (SOA) and Raman amplifier are the most common optical amplifiers used in optical communication. Optical amplifiers are designed by doping of rare earth elements like Erbium, Ytterbium and Thallium into optical fibers to operate in different wavelengths from 0.5 μm to 3.5 μm . Amplifier's operating wavelength, gain bandwidth and other relative characteristics

can be determined by the dopants instead of fiber material. An EDFA is, by far, the most widely used fiber amplifier, because EDFA is capable of amplifying all the wavelengths ranging from 1500 nm to 1600 nm [18]. SOA is very similar to a laser except that it has no reflecting facets. The weak signal is incident on the active region of the SOA and due to stimulated emission, the signal is amplified. In Raman amplifiers, the optical fiber itself is used as a gain medium making it cost effective. In this amplifier, the amplification is performed using a nonlinear effect called Raman scattering with high pump power phenomena without using expensive doped ions [19]. The table 1.2 shows a comparison of different optical amplifiers.

Table 1.2: Different optical amplifiers characteristics

Features	EDFA	SOA	Raman
Wavelength of Operation	1525 nm-1565 nm	Any (but limited to < 50 nm bandwidth)	Any, depend on pump wavelength and power
Gain	>20 dB	>20 dB	5-15 dB
Gain Bandwidth	10 nm-40 nm	20 nm-50 nm	20 nm-40nm
Noise	Low	Low	Very low
Bias Current	>100mA	50mA	>500mA
Directions	Unidirectional and bidirectional	Unidirectional and bidirectional	Unidirectional and bidirectional
Losses	<1 dB	5-6 dB	<1 dB
Polarization sensitivity	0 dB	>few mW	0 dB
Optical Pump Wavelength	980nm, 1400 nm-1500 nm	NA	Stoke shift below signal
Optical Pump Power	20 mW-50 mW	NA	100mW- 200mW

1.2.8 Light Emitting Diodes (LEDs)/ Light Amplification through Stimulated Emission of Radiations (LASERS): Various light sources are the key components for generating the carrier to transmit the signal in optical communications. When an atom is excited to move from one energy level to higher energy level, emission of light produced by this atom in coming back to the initial energy level. In LED's this emission is spontaneous in nature and in lasers, it is stimulated emission [20]. A variety of light sources are commercially available such as Injection-locked Fabry-Perot lasers,

Continuous Wave (CW) lasers, Tunable lasers, Vertical Cavity Surface Emitting Diodes (VCSEL) etc.

1.2.9 Requirements of PON Systems

1.2.9.1 Enhancement of Capacity of the Network: The existing WDM network with large spacing wavelengths can be converted into DWDM network by multiplexing these wavelengths with narrower spacing without disturbing the existing fiber [21].

1.2.9.2 Optimization of Existing Networks: The number of users can be increased by reducing the channel spacing but it also increases interference due to overlapping of the signals in the channel. So, there is requirement to optimize amplifiers and other components to utilize maximum bandwidth and receiver capability.

1.2.9.3 Scalability: The network should be able to scale in next generation networks for large bandwidths and capacity.

1.2.9.4 Compatible and Flexible: The network should be effective and flexible to fit to adopt new technology.

1.2.9.5 Integration: The integration of the network with smart traffic planning is required to achieve a good quality of service.

1.2.9.6 Immune to Interference: The network should be lossless network and immune to the interference produce by the same or different media.

1.2.9.7 Miscellaneous: The network should be secure and robust. Also, the overall cost of the network should be low.

1.3 Switching in Passive Optical Networks

The collection of devices that subscribers employ for communication is known as station. A network is a set of interconnected stations with transmission paths. For data transmission from source to destination, switching is used. To perform the switching in PONs, switches are used. A switch is a device to establish temporary connections between the devices to provide a link for communication between them [22]. The three main types of switching are as follows:

1.3.1 Circuit Switching: In the circuit switching, firstly a connection is established and then data is transmitted from source to destination at the physical layer. The permanent link is established up to the completion of data transfer entirely. Information transferred between the source and destination is not packetized. There is a continuous flow of information between the source and destination station in a scheduled time, although

there may be periods of silence. The main advantage of circuit switching is that there is no requirement of header (for addressing) during data transfer [23].

1.3.2 Packet Switching: The packet switching is a connectionless switching. The information is sent in the forms of packets. So, the permanent connection or reserve path/ bandwidth is not required for this type of switching. Also, the time is not fixed for processing of packets i.e. they can transmit at any time. The allocation is performed on first come, first serve basis. The packet switching is of two types:

1.3.2.1 Datagram Switching: In this type of switching, the packets are sent out independently called as datagrams. The network treats each datagram as individual even if it is a part of a multi packet transmission.

1.3.2.2 Virtual Circuit Switching: The virtual switching has both type of advantage of circuit switching and datagram switching. In this, firstly a virtual connection is established and then information is sent in the form of packets. All the packets having identical source and destination will move through the same link path. Due to resource allocation is on demand; it may be possible that the packets will arrive at the destination with different delays.

1.3.3 Cell Switching: In the packet switching, the size of the packet may vary upto 65000 bytes. This size is too large to send. Also, this switching is not economical to send such type of packet as loss of data can be possible. Cell switching is used to overcome this problem. In the cell switching, the information is sent in the form of small packets. In this the packet size is as small as of 53 bytes. This switching is also connectionless switching and provides a high speed of 155.52 Mbps [24].

1.4 Summary

The optical fiber communication system and passive optical networks are introduced. The various standards of passive optical networks such as BPON, EPON, G-EPON, 10 GPON have been discussed. From the system perspective, the various configurations of passive optical networks based upon multiplexing techniques have also been described. The hybrid (WDM/ TDM) PONs have the advantages of both multiplexing techniques and recommended to fulfill the requirement of higher data rate transmission with utilizing the larger bandwidth to the end users. Various components and system terminology of PONs are explained in details. We believe that the hybrid passive optical networks should be

regarded as a best contender for future high-capacity access networks which can efficiently utilize the enormous bandwidth of optical communication system.

Chapter 2

Literature Review and Outline

2.1 Introduction

In this chapter, we present a comprehensive literature review of Passive Optical Networks (PON). In the fiber optic communication, as large number of channels are transmitted in same fiber through various multiplexing techniques. Wavelength Division Multiplexing (WDM) which makes a single strand of fiber act as many virtual fibers. WDM has allowed the capacity of fibers to be increased by more than two orders of magnitude over the past few years, providing plenty of bandwidth to fuel the growth of data traffic and the Internet in optical networks. The optical amplifiers have permitted the revolution associated with WDM in optical networks [8]. Because a number of channels could be simultaneously amplified, the cost of deploying more wavelengths in WDM was gated by the terminal end cost rather than the regenerator cost. The full utilization of bandwidth to satisfy the future bandwidth demands, overall expenditure, high speed data rates and scalable architecture are the important decisive factors.

The repeaters or optoelectronic regenerators were used to transmit the high speed data over large distance. Due to Optical-Electrical-Optical (O-E-O) conversions, these are not feasible and more expensive with the increase in the data rate and channel capacity. The optical amplifiers are advent to overcome repeater constraints. The basic parameters to determine the performances of PONs are Bit Error Rate (BER), Q-factor, Signal to Noise Ratio (SNR), different types of modulation format used, received power, type of PON standards and architecture used. PON systems experience different crosstalk such as Rayleigh Scattering (RS), Brillouin Scattering (BS), Self Phase Modulation (SPM) and Cross Phase Modulation (XPM). Various authors have worked in this area. The work done and the results from the literature on various PON architectures, amplifiers, crosstalk analysis and topologies have been summarized in the following sections.

2.2 Architectures of PON

Mozhgan Mahloo et al. [25] examined and reported the comparative study of Active Optical Network (AON), WDM PON and hybrid Time Division Multiplex/ Wavelength Division Multiplex (TDM/WDM) PON. They have proposed these network architectures to provide Point to Point (P2P) video services. The architectures of APON, WDM PON

and hybrid PON are analyzed for 32, 64 and 128 number of users with 100 Mbps, 1 Gbps and 10 Gbps data rate respectively. These networks are compared for average traffic load, switching capability and power consumption. The interesting findings also validated the assumption and subsequent work done in this regard and shown that hybrid PON is the best solution for next generation networks.

Salem Bindhaiq et al. [26] reported hybrid (TDM/ WDM) PON as Next Generation (XG) networks because of enormous bandwidth capacity, high speed data and compatibility to existing Optical Distribution Networks (ODN). The comparison between 10 GE-PON, XG PON 1 and XG PON 2 has been given. Their analysis related the results in terms of eye diagrams, BER to received optical power over 50 Km fiber length.

Chang-Chia Chi et al. [27] proposed a reliable TDM PON system. Different architectures using 1:16 and 1:32 split ratio for 168 Optical Network Units (ONUs) over 10 Km distance have been demonstrated. A fault location scheme to find out the failure in the system had also been proposed. The Fabry–Perot (FP) laser diodes at 1625 nm wavelength were employed in the system.

Han Hyub Lee et al. [28] proposed architecture of WDM PON based on Pre-spectrum Sliced Seed Lights (PSSL) with 50 GHz channel spacing. The system was proven as cost effective due to reduction in the seed light cost. The backward Amplified Spontaneous Emission (ASE) light has been analyzed with EDFA for 64 channels at 1.25 Gbps data rate over 20 Km distance.

Kwanil Lee et al. [29] reported a simple, colorless and polarization independent WDM PON using SOA. The wavelength conversion has been achieved by spectrum sliced technique. The system was analyzed for power budget of injection ASE with 155 Mbps to 1.25 Gbps data rate at 100 GHz channel spacing over 25 Km transmission distance.

Chien-Hung Yeh et al. [30] investigated experimentally a bidirectional TDM PON system for upstream (1310 nm wavelength) and downstream (1490 nm wavelength) with 2.5 Gbps data rate over 20 Km distance respectively. The system is analyzed for different CW injection powers, BER and received output powers.

Seung-Hyun Cho et al. [31] proposed architecture of WDM PON system with 16 numbers of users using decision threshold device and Reflective Semiconductor Optical Amplifier (RSOA) at the receiver end at 1.25 Gbps data rate with 200 GHz channel spacing. The system performance was enhanced in terms of injection powers (-24 dBm) and power penalty (1.6 dB) for the upstream transmission.

Luís Gouveia et al. [32] proposed flexible topology architecture of PON for 64 number of ONUs using 1:8 splitters. The system was based upon Integer Linear Programming (ILP) algorithm to find out the location of installation of splitter and the interconnection mechanism of all the parts of the network such as CO, fibers and ONUs etc.

Stephan Jay et al. [33] compared different topologies of PON architectures. The analysis has been done on the basis of cost of the network for transmission of voice, broadband, IP-TV yearly basis in Ethernet P2P, WDM PON, GPON (P2P) and GPON Point to Multipoint (P2MP) scenario. The performance of two approaches (steady state and dynamic) was discussed and compared in details.

Abhishek Dixit et al. [34] analyzed an energy efficient and flexible bidirectional hybrid (TDM/ WDM) PON system for cost, power consumption and distance. The system was investigated for required number of wavelengths, network load and delay in different RN's structures based on cascaded configuration of Array Waveguide Grating (AWG) only, Wavelength Selective Switch (WSS) only, AWG and WSS combined.

Brigitte Jaumard et al. [35] proposed a cost effective hybrid (WDM/ TDM) PON optimization scheme. A mathematical model was proposed to find out the solution for the best suitable placement of splitters, AWGs and ONUs. The system was analyzed for 128 numbers of ONUs. ONUs have been divided into number of clusters and then switching equipment is assigned to the cluster on the basis of total number of ONUs and locations as per the model.

Burak Kantarci et al. [36] investigated PON with bandwidth distribution schemes over 20 and 100 Km distances. The bandwidth utilization for upstream transmission has been achieved through multi-thread polling and two-stage buffering scheme. The proposed scheme was fast as compared to other existing schemes. Two buffers depending upon the upstream request has been installed to reduce the overall delay.

Khan Ahmed Muddassir et al. [37] proposed bidirectional hybrid (WDM/ TDM) PON using Differential Quadrature Phase Shift Keying (DQPSK) modulation scheme using Inverse Return-to-Zero (IRZ) data format. The data speed of 2.5 and 10 Gbps for uplink and downlink has been achieved with 10 number of ONUs over 20 Km distance at 50 GHz channel spacing respectively. A re-modulation scheme was also used to avoid the laser source at the ONU end.

M. A. Elmagzoub et al. [38] proposed two architectures of hybrid and stacked PON. 4 channels at 40 Gbps data rate with 1490 nm and 1330 nm center wavelengths and 100

GHz channel spacing for downlink and uplink have been transmitted and received at 50 Km distance with 32, 64 and 128 number of ONUs respectively.

Vishal Sharma et al. [39] proposed EPON using OFDM-DWDM technique. 16 numbers of ONUs were accessed at 1.25 Gbps data rate to a single channel over 20 Km fiber length. Various result parameters like SNR over different fiber lengths at various optical input powers for the proposed scheme have been discussed in detail.

Redhwan Q. Shaddad et al. [40] proposed hybrid (WDM/ TDM) PON architecture using Wireless Fidelity (Wifi) and Wireless Interoperability for Microwave Access (WiMAX) techniques. Proposed system was investigated at 2.5 data rate for 32 numbers of ONUs over 24 Km fiber length with 54–30 Mb/s data rate over 5 Km wireless network.

Abdel Hakeim M. Husein et al. [41] proposed WDM PON using AWG demultiplexer with spectrum slicing technique for 32 number of ONUs. The system was investigated for 3 Gbps data rate over a distance of 40 Km with 50 GHz channel spacing. Various results for BER with respect to received output power and eye diagrams have been shown.

Komal Preet Kaur et al. [42] investigated WDM PON for different types of filters such as Integrator, Gaussian, Bessel, Chebyshev, Inverse Chebyshev, Butterworth, Elliptic and Rectangular filters with four WDM channels at 10 Gbps data rate for 100 GHz channel spacing. The results were shown that a good BER and Q factor were achieved by Bessel filter than other filters.

Fenfei Hou et al. [43] analyzed theoretically hybrid (OCDM/WDM) PON system using DQPSK modulation scheme. The proposed system was very simple which avoid the complexity of CDMA encoder and decoders. The system was investigated for four channels of WDM at 5 Gbps data rate over 20 Km transmission distance.

Amandeep Kaur et al. [44] investigated asymmetric bidirectional GPON architecture for various data formats. The data rate of 10 Gbps for downstream at 1570 nm wavelength and 2.5 Gbps for upstream at 1270 nm wavelength has been transmitted and received through 4 WDM number of channels over 95 Km distance with 50 GHz channel spacing.

P. K. Chowdhury et al. [45] proposed WDM PON using RSOA and Orthogonal Frequency Division Multiplexing (OFDM). The data rate of 10 Gbps at 1550 nm wavelength has been transmitted to 256 number of ONUs over 60 and 85 Km fiber link at 100 GHz channel spacing. The system was investigated for flat power allocation in OFDM signaling.

Abdullah O. Aldhaibani et al. [46] investigated hybrid (WDM/ TDM) GPON using Radio Over Fiber (ROF) technique and DPSK modulation scheme. The system has been investigated for 32 and 64 number of ONUs at 2.5 Gbps data rate over a distance of 25 Km. Various parameters such as eye & constellation diagrams, BER, OSNR etc. have been shown to verify the results.

A. J. Mendez et al. [47] investigated that, for Direct Detection of Amplitude Modulation (AM) on/off keying type optical signals, a spread spectrum multi-access system showed better results. The research was performed by designing codes and strategies for its applications to dense, high-speed optical network. The overall performance of the network was examined and reported.

2.3 Optical Amplifiers in PON

Paweł Czyżak et al. [48] studied DWDM system using quantum-dot pumping lasers. The authors have also highlighted the impact of Raman amplifier using single and double pump configurations. 17.7 dB gain and 4.5 dB noise figure have been achieved. The relation of gain with various parameters like fiber length, wavelength, pump laser current, pump power, output power has been shown. Also, the comparison of Raman amplifier and SOA has been presented.

P. Parolari et al. [49] proposed a WDM PON architecture based on Reflective RSOA. Various types of GSM (Global System for Mobile Communications) and WCDMA (Wideband Code Division Multiple Access) data with 2.5 Gbps to 10 Gbps speed are analyzed using self-tuning colorless transmitter. 3×10^{-3} BER was achieved at 52 Km distance with 10 Gbps data rate.

R. Q. Shaddad et al. [50] outlined various standards of PON like BPON, EPON and GPON. Different terminologies of WDM PON, TDM PON, OFDM PON and hybrid (WDM/TDM) PON have been discussed. Proposed system was also embedded with wireless access technologies like WiFi and WiMax. Differences and similarities of these standards have been reviewed and compared in detail.

Lijun Li et al. [51] presented PON system based on OFDM coding technique with better transmission efficiency. Four and eight OFDM subcarriers are assigned to transmit 40 Gbps data rate over 20 Km distance. Various performance parameters like Q and BER were shown for misaligned time and received optical power to verify the results.

Kwang-Ok Kim et al. [52] proposed an energy efficient colorless bidirectional hybrid (TDM/ WDM) PON system with 32 numbers of users using RSOA for 2.5 Gbps data

rates at 100 GHz channel spacing over 50 Km distance. The proposed network was very similar to GPON standard G.984.x. An injection power of -17 dBm has been achieved for upstream and downstream for the proposed architecture.

Chin-Feng Su et al. [53] proposed a bidirectional colorless WDM PON system with 32 numbers of Multi Wavelength Light Sources (MWLS) with EDFA for 1.25 Gbps data rate at 100 GHz channel spacing over 25 Km distance. The system used very low pump power by narrowing the bandwidth of the laser sources. They have shown that the proposed scheme was better than BLS system with constant pump power.

Idelfonso Tafur Monroy et al. [54] investigated bidirectional PON using RSOA with 10 Gbps data rate over 80 Km distance. Distribute Raman Fiber Amplifier (DRFA) with 0.7 dB power penalty was used as backward pump and forward pump to boost up the signals to large distance.

Gaurav Pandey et al. [55] presented bidirectional colorless WDM PON using Sub Carrier Modulation (SCM) technique with RSOA. Sixteen upstream and downstream channels at 10 Gbps data rate were investigated over a distance of 20 Km with 80 GHz channel spacing. 20 GHz subcarrier radio frequency was taken with 60 mA biasing current at 1554-1564 nm pump wavelength bands of RSOA.

Deeksha Kocher et al. [56] investigated different PON standards with different data rates using Travelling wave Semiconductor Optical Amplifier (TSOA). The system was analyzed for 32 and 64 numbers of ONUs at 1330nm and 1550 nm wavelength for uplink and downlink respectively over 50 Km fiber link length.

Yanan Cao et al. [57] investigated bidirectional hybrid (WDM/OCDMA) PON system using RSOA. The system was investigated for crosstalk penalties due to neighboring channels codes. Sixteen WDM channels were used to transmit and receive the data at a speed of 1.25 Gbps over 22 Km fiber length.

R. S. Kaler et al. [58] reported the impact of EDFA power on optical systems. The performance of optical communication systems with subsequent increase in different types of fibers used in optical systems was also examined. The need of accurate toning among the EDFA power and fiber link for best result was highlighted.

Delavaux et al. [59] demonstrated the two efficient hybrid EDFA structures as power booster. The two simulations pumps (tuned at 980 nm and 1480 nm) were used to pump the proposed amplifier. The amplifier was provided large gain over broad spectrum (> 35 nm) with better gain flatness (i.e. 1 dB) and output power (17 dBm approx.). They carried

out a hybrid pumping scheme to avoid inter-channel crosstalk effect for pumps of the same wavelength with different pumping power.

In Raman amplifier, it is better to use single pump wavelength instead of multiple pumps because: (i) it is easy to design with minimum cost and (ii) the profile of the Raman gain spectrum is independent to channel loading. Among these two, the second point is very important because the gain shape of saturated Raman amplifier with multiple pumps can be complex function of the present channels. Bolshtyansky et al. [60] demonstrated the hybrid flat or tilt free amplifier in a new wavelength range (i.e. L+ band ranging from 1610 nm to 1640 nm) using a single pump tuned at 1536 nm. It was suggested that, to reduce the micro-bend losses, the Raman gain media should be improved by optimizing the parameters.

Lee et al. [61] demonstrated the new hybrid optical amplifier in which the pumped Dispersion Compensated Fiber (DCF) as Raman amplifier was used with the EDFA in cascaded way and further characterized in the terms of gain and noise figure.

2.4 Nonlinearities Induced in PON

The optical networks are also moving towards the switching systems (such as packet or burst switching). Due to the switching techniques, the power per channel varies and this variation causes the transients on other channels propagating in the same fiber. To suppress this undesired effect, many control methods are suggested in literature.

A. Kokangul et al. [62] have demonstrated a PON using four primary and twenty secondary locations in the city of Adana (Turkey). They have implemented the system using genetic algorithm and some mathematical models. Also, the attenuation and other non linearity have been considered in detail.

Josep Prat et al. [63] experimentally proposed PON system using ring – tree architecture with 32 channels to transmit data at 10 Gbps speed up to 100 Km fiber length. RSOA was used to transmit the uplink data. TDM PON, WDM PON, TDM/ WDM PON and Scalable Advanced Ring based passive Dense Access Network Architecture (SARDANA) have been analyzed for cost and fiber length with respect to number of ONUs.

Jongdeog Kim et al. [64] proposed a bidirectional hybrid (TDM/ WDM) PON system using 10 Gbps data rate as downstream and 2.5 Gbps as upstream over 60 Km distance respectively. Various ITU-T and IEEE PON standards have been compared in terms of

Burst Mode Sensitivity (BMS). The system is simulated and analyzed for power budget feasibility and optical path loss.

Seung-Hyun Cho et al. [65] analyzed inter-ferometric crosstalk persuaded in bidirectional WDM PON using RSOA. They have proposed a Distributed Feed Back (DFB) laser source with polarization controller, 50:50 coupler and a mirror to seed light source. Power penalty with signal to crosstalk ratio for different feedback combinations have been discussed to show the enhanced system performance in terms of crosstalk.

Ju Han Lee et al. [66] analyzed theoretically bidirectional WDM PON using RSOA with nonlinearity effects such as Rayleigh backscattering and injection powers for 622 Mbps data rate at 100 GHz channel spacing over 60 Km distance. Their analysis was related to the results in terms of eye diagrams, BER to received optical power over a range of fiber lengths.

Soo-Jin Park et al. [67] analyzed Rayleigh backscattering and the intensity noise in WDM PON with 1.25 Gbps over 20 Km distance. They employed RSOA as modulator in the proposed system. A re-modulation scheme by splitting and sharing the optical power of CW laser source was also proposed. The spontaneous noise and chromatic dispersion was mitigated by injecting the light directly to RSOA in spite of slicing lasers sources.

Abdelfettah Chenika et al. [68] proposed bidirectional WDM PON using NRZ-DQPSK modulation scheme for upstream and ASK (Amplitude Shift Keying) modulation scheme for downstream. Four channels of 10 Gbps have been transmitted over 30 Km optical fiber length. The system has also been analyzed for the effect of Rayleigh and Brillouin backscattering.

Meihua Bi et al. [69] proposed ultra-dense WDM-PON using Tunable Optical Filter (TOF). The system was investigated for twelve numbers of ONU at 1.25 Gbps data rate with different channel spacing. The effect of nonlinearity like Four Wave Mixing (FWM) has been analyzed and mitigated for the proposed system by aligning the signals of all the channels with respect to the channel spacing.

Yue Shi et al. [70] analyzed self-homodyne WDM PON using DQPSK modulation scheme and simple and low cost intensity detection. The effect of chromatic dispersion and polarization crosstalk on the proposed system has been investigated and mitigated by using 50% RZ polarization modulation format at 43 Gbps data rate over 60 Km fiber length.

Taniguchi et al. [71] presented a novel technique to multiplex the huge number of channels in ultra-dense DWDM phenomena (called super-DWDM) at reduced channel spacing. Further, the performance degradation has been observed due to the induced undesired crosstalk between those compact channels. They analyzed and estimated the performance of the proposed technique by different steps. In the first step, the analytical calculation has been done to find the relation between filter bandwidth and the sweep range per channel, which resembles to the channel spacing. Then in the second step, they assessed that the achievable number of channels yielded the multichannel WDM signals. In the investigation, the optical filters were used with a bandwidth of about 10 GHz.

Li et al. [72] investigated the performance of return-to-zero-differential phase shift keying (NRZ-DPSK) modulated DWDM system with saturated SOA. By introducing time interleaving, they suppressed the crosstalk induced by SOA nonlinearities and WDM component. It was reported that by providing proper time delay between the even and odd channels, the induced linear crosstalk could be mitigated. To reduce the Self Phase Modulation (SPM) and Cross Phase Modulation (XPM), the time interleaving strategy was used in which the intensity summed over all the channels were constant.

Yunfeng Shen et al. [73] studied WDM optical system for the effect of coherent and noncoherent crosstalk via Optical Cross Connect (OXC) nodes. Depending on the relationship between the time interval of one bit of the signal and propagation delay differences, coherent crosstalk originated noise with the fluctuation of signal power. The crosstalk effect was mitigated in the systems with dissimilar scales.

Xiangnong Wu et al. [74] presented an analytical model of intra band crosstalk in an $N \times N$ Fiber Bragg Grating (FBG) and circulator based OXC and showed that the coherent crosstalk of worst case was 22–26 dB, based on the 2x2 OXC switching state. Moreover, a unique design of OXC with better performance of intra band crosstalk was proposed.

An Vu Tran et al. [75] proposed three novel Optical Add Drop Multiplexer (OADM) techniques with simple & compact design and excellent crosstalk performance. The optical add drop multiplexer used a single MOC & either one or two narrow-band FBGs, based on the crosstalk conditions.

A. Tzanakaki et al. [76] simulated the WDM system using OADM. The performance of networks was enhanced using optical filters by minimizing the nonlinear effects. It was shown that cyclic filtering could eliminate the spectral broadening imposed by the Kerr nonlinearity. The penalty associated by various results to recognize the optimum

operating regimes in terms of filter bandwidths and power for optical add drop multiplexer-chain WDM networks were described in detail.

2.5 Different Topologies based PON

Yejun Liu et al. [77] simulated long reach PON architecture with protection scheme. They have analyzed the network for single Shared-Risk Link Group (SRLG) failure. The two algorithms based on Backup Fibers Protection (BFP) have been proposed to make the network reliable in case of any connection failure. The data is sent through backup fibers with optimum delay in failure.

Lei Shi et al. [78] proposed long reach PON architecture using AWG and EDFA. They have analyzed ring and tree architectures of PON system for wavelength allocation scheme. A mathematical model for BER was analyzed for calculating the consequence of AWG and EDFA on the overall system performance. Various performance parameters like channel numbers, wavelength assignment schemes, wavelength numbers with respect to BER have been discussed in detail.

Stamatios V. Kartalopoulos et al. [79] demonstrated hybrid (CWDM/ TDM) PON hierarchical system with 200 GHz channel spacing. The network was flexible and scalable in term of topologies. The performance of proposed system was described for 16 to 18 channels of Ethernet, video, data and telephony services to 8 Km distance. Various results of BER, Q factor with respect to fiber length for various input power levels have been shown to analyze the system.

Chuan-Ching Sue et al. [80] proposed a WDM PON with full protection scheme. The scheme was implemented to defend feeder fiber and distribution fiber both. The scheme was discussed in detail with timing diagrams, path configurations, flow charts of operations. They have also compared their scheme with existing PON standards and other schemes from the literature.

Simranjit Singh et al. [81] proposed WDM PON based on hybrid (ring-tree-star) topology. The system was investigated for 2048 number of users which were connected through eight OADMs and SOAs. Various results have been shown in terms of eye diagrams, BER and Q factor for channel spacing, output power and fiber lengths.

Lei Tang et al. [82] proposed an OFDM PON with full protection scheme. The scheme was proposed to defend feeder fiber and distribution fiber. The system also investigated for Rayleigh backscattering and crosstalk effects. The schemes are discussed in detail

with path configurations and flow charts of operations. They have also compared their scheme with the literature.

Chenwei Wu et al. [83] proposed a self-healing WDM-PON architecture using Raman amplifier. A fault protection scheme has been proposed for feeder fiber and distribution fiber for 150 number of ONUs. The system was also investigated for insertion losses due to AWG, FBG, 3D coupler and circulator for three wavelength channels at 2.5 Gbps data rate.

Benyang Chen et al. [84] proposed ring topology based WDM PON using dynamic wavelength assignment technique. A feeder fiber was used to provide the protection to the ring architecture. The performance of various components like AWG, coupler, splitter, fiber and optical switch was investigated in terms of insertion loss.

Yang Qiu et al. [85] demonstrated ring hybrid (WDM/ TDM) PON architecture using AWGs. A protection for the failure of feeder fiber, distribution fiber and the ring architecture was also proposed. The scheme was investigated for 16 ONUs at 5 Gbps data rate over 20 Km distance.

Rachna Asthana et. al [86] reviewed protection and restoration schemes. A path protection scheme was proposed to improve resource utilization at the cost of more computational density. The physical level failure was recovered in the optical layer schemes to avoid the severe problem of fault multiplication in the higher layer. Higher layer schemes were used to recover higher layer node or single link failures.

As shown in the literature survey, the researchers have contributed heavily in the designing of passive optical networks. The progress in the field of passive optical networks is presented in table 2.1.

Table 2.1: The progress in PON

References	PON technique	Number of ONUs	Downlink Data rate	Uplink Data rate	Distance in Km	Spacing in GHz
Mozhgan Mahloo et al. [25]	WDM/ TDM PON	128	10 Gbps	1 Gbps	60	-
Salem Bindhaiq et al. [26]	WDM/ TDM PON	64	10 Gbps	1 Gbps	50	-
Chang-Chia Chi et al. [27]	TDM PON	168	1 Gbps	1 Gbps	20	-
Han Hyub Lee et al. [28]	WDM PON based on PSSL	64	1.25 Gbps	1.25 Gbps	20	50
Kwanil Lee et al.	WDM PON using	16	1.25 Gbps	1.25 Gbps	25	100

[29]	SOA					
Chien-Hung Yeh et al. [30]	TDM PON	2	2.5 Gbps	2.5 Gbps	20	-
Seung-Hyun Cho et al. [31]	WDM using RSOA	16	1.25 Gbps	1.25 Gbps	1.25 Gbps	200
Khan Ahmed Muddassir et al. [37]	WDM/ TDM based on DQPSK with IRZ	10	10 Gbps	2.5 Gbps	20	50
M. A. Elmagzoub et al. [38]	Hybrid and stacked PON	128	10 Gbps	10 Gbps	50	100
Vishal Sharma et al. [39]	OFDM-DWDM	16	1.25 Gbps	Unidirectional	20	25
Redhwan Q. Shaddad et al. [40]	WDM/ TDM PON using Wifi and WiMAX	32	2.5 Gbps	2.5 Gbps	24	100
Abdel Hakeim M. Husein et al. [41]	WDM PON using AWG	32	3 Gbps	Unidirectional	40	50
Komal Preet Kaur et al. [42]	WDM PON for different types of filters	4	10 Gbps	Unidirectional	20	100
Fenfei Hou et al. [43]	OCDM/WDM PON system using DQPSK	4	5 Gbps	Unidirectional	20	50
Amandeep Kaur et al. [44]	Bidirectional GPON	4	10 Gbps	2.5	95	50
P. K. Chowdhury et al. [45]	WDM PON using RSOA and OFDM	256	10 Gbps	1 Gbps	85	100
Abdullah O. Aldhaibani et al. [46]	WDM/ TDM GPON using ROF and DPSK	64	2.5 Gbps	Unidirectional	25	100
P. Parolari et al. [49]	WDM PON using RSOA	-	10 Gbps	5 Gbps	52	100
Lijun Li et al. [51]	OFDM PON	8	40 Gbps	2.5 Gbps	20	100
Kwang-Ok Kim et al. [52]	TDM/ WDM PON using RSOA	32	2.5 Gbps	2.5 Gbps	50	100
Chin-Feng Su et al. [53]	WDM PON using MWLS with EDFA	32	1.25 Gbps	1.25 Gbps	25	100
Gaurav Pandey et al. [55]	WDM PON using SCM technique	16	10 Gbps	10 Gbps	20	80

	with RSOA					
Deeksha Kocher et al. [56]	WDM PON using TSOA	64	10 Gbps	Unidirectional	50	100
Yanan Cao et al. [57]	WDM/ OCDMA PON system using RSOA	16	1.25 Gbps	1.25 Gbps	22	-
Josep Prat et al. [63]	TDM/ WDM PON using RSOA	32	10 Gbps	1 Gbps	100	50
Jongdeog Kim et al. [64]	TDM/ WDM PON	8	10 Gbps	2.5 Gbps	60	200
Ju Han Lee et al. [66]	WDM PON system using RSOA	3	622 Mbps	622 Mbps	60	100
Soo-Jin Park et al. [67]	WDM PON system using RSOA	-	1.25 Gbps	1.25 Gbps	20	-
Abdelfettah Chenika et al. [68]	WDM PON using NRZ-DQPSK	4	40 Gbps	10 Gbps	30	200
Meihua Bi et al. [69]	WDM-PON using TOF	12	1.25 Gbps	1.25 Gbps	80	100
Stamatios V. Kartalopoulos et al. [79]	CWDM/ TDM PON	18	2.5Gbps	2.5 Gbps	8	200
Yang Qiu et al. [85]	WDM/ TDM PON using AWG	16	5 Gbps	5 Gbps	20	-

As per the literature survey given in Table 2.1, the most of the work is carried out for WDM, TDM individually and combinations of these techniques in the field of PON systems. The researchers proposed various PONs using symmetrical or different downstream and upstream data rates varies from 1.25 Gbps to 10 Gbps over to 100 Km maximum reach. 25 GHz to 100 GHz channel spacing is achieved for designing of PONs for 4 to 256 numbers of ONUs with maximum acceptable BER.

2.6 Gaps in the Present Study

This section lists the common limitations encountered while dealing with hybrid (WDM/ TDM) PON. This would realize the importance of the drawbacks and explicate the reasons for attempts to attain solutions to these problems. Based on the research literature, it is observed that there is a continuous need of the advancement in optical networks, which can operate at higher user data rates with large cardinality. More efficient and

compact solutions can be implemented by using PONs on such networks. These are attractive access networks solution with the advantage of low running cost and enormous bandwidth. A limited work has been carried out for the designing of architectures of hybrid PON systems. It is perceived that number of users, type of modulation scheme, data format and switching techniques directly decide the performance of system. The fiber installation cost is a very important factor for designing of ONUs for improving efficiency of the network. The design and performance analysis to increase the number of users is not done in detail. For a total successful PON deployment, the network system should be simple, robust, flexible and cost effective for the final customer.

The nonlinearity can be restricted by efficient designing of unique optical architectures to accommodate more number of ONUs. Various amplifiers have also not been properly investigated for achieving long reach networks. Proper amplification is needed to enlarge the number of ONUs and to transmit the data to longer distance. In literature, various amplifiers are proposed for TDM PONs and WDM PONS, but the work over amplifiers for the hybrid system has been rarely discussed. Up till now, the error free performance with 3dB gain was obtained for TDM and WDM PON systems. To improve survivability of optical network systems, more work needs to be carried out to implement different architectures based on vast available network topologies. Till now, investigation of hybrid PON system has been carried out for lesser number of ONUs at relatively low bit rate and wider channel spacing. Hence, there is a need to identify a WDM/ TDM compatible optical network system which can operate at higher data rates to facilitate different types of user data with acceptable BER and reduced crosstalk. The capacity of a hybrid PON can be improved for multicasting with implementing different cost effective topologies. The ring architecture is proposed for the WDM/TDM PON systems, but architectures based on combination of various topologies have been rarely designed.

The main scenario mentioned above for performance analysis of hybrid optical networks includes certain definite & important guidelines that will revamp the PON network.

2.7 Objectives

Keeping in view the above mentioned aspects, the objectives of research were formulated which are listed as follows:

1. To propose the new architecture of hybrid passive optical network to improve the efficiency of optical network unit (ONU) with cost effective and subsistence.

2. To investigate and compare hybrid passive optical network system with amplifiers find out the best suitable amplifier for acceptable bit error rate performance.
3. To propose analytical model for performance evaluation in PONs take into account noise and impairments and investigate the techniques to minimize these effects.
4. To improve and compare the system performance in terms of bit rate & increase in maximum number of users by designing the hybrid PON with different topologies.

2.8 Outlines of Thesis

The thesis has been organized into seven chapters. The content of each chapter is briefly described below.

After introducing hybrid passive optical networks and their types in Chapter 1, the literature survey of hybrid passive optical networks, problem formulation and objectives are presented in Chapter 2. Further, the organization of the thesis is presented.

Chapter 3 deals with the first objective which is to propose the new architecture of hybrid passive optical network to improve the efficiency of optical network unit with cost effective and subsistence. A hybrid PON using triple play services (video, voice and data) is simulated for 128 ONUs. The system is investigated for suitability of various data formats. NRZ rectangular data format was found as the most suitable data format for the proposed network. Further, a bidirectional hybrid PON for 128 ONUs has been investigated for different data rates i.e. 1.25, 2.5, 5 and 10 Gbps. To implement bidirectional transmission in a single fiber, a circulator is inserted to separate the uplink signals from downstream data. The effect of crosstalk between uplink and downlink signals is alleviated by using different wavelengths i.e. 1300 nm and 1550 nm wavelengths respectively.

In the next Architecture, a network based on cost effective technique i.e. Common Carrier for All Optical Network Units (CCAONUs) is proposed. A carrier is stimulated at the central office (CO) and remodulated for upstream transmission at the subscriber end for making ONU very simple and cost effective. It is found that the signal with 10 Gbps data rate can be transmitted and received up to 190 and 185 Km distance for 256 ONUs with minimum acceptable Q factor without any inline amplification respectively. Further, an architecture using four aggressive schemes i.e. No Buffer (NB), With Buffer (WB), Reduced Buffer (RB) and Reduced Buffer with Small Packet (RBSP) is also proposed.

We have analyzed all these proposed schemes for downstream and upstream by exploring the relationship between power consumption and average traffic load. The “RBSP” scheme has shown a reduction of more than 35% of total leakage power at the central office with the compromise of delay in packets receiving.

Chapter 4 is based on second research objective, i.e. to find out the suitable amplifier for hybrid PON system. In this chapter, we have proposed bidirectional hybrid (WDM/TDM) PONs for Raman, SOA and EDFA amplifiers using polarization modulation technique in swing with QAM at 5 and 10 Gbps data rate. BER, Q factor and received optical power are observed for EDFA, SOA and Raman amplifiers in this model at 50 and 80 Km distances for 10 and 5 Gbps data rates respectively. It has been observed that EDFA amplifier shows better performance than SOA and Raman amplifiers.

Chapter 5 deals with third research objective which is to analyze and mitigate the effect of nonlinearity in the PON systems. We have investigated bidirectional hybrid PON using CCAONUs technique. The system is analyzed theoretically in the presence of crosstalk due to fiber nonlinearities like XPM, FWM, SRS and SBS. Various results in 2D and 3D are shown for the impact of these nonlinearities with Carrier to Noise Ratio (CNR), input power, received output power, BER and number of ONUs. The impact of non linearity like RS and SBS is mitigated in this architecture. Further, we have designed network for Mixed Line Rates (MLRs) for 10/ 20/ 40 Gb/s to meet the requirement of high volume of heterogenic traffic. The investigation is focused on uniform channel spacing and mixed channel spacing for MLRs.

Chapter 6 represents the fourth objective of this thesis, i.e. to increase the number of users in hybrid PON system with different topologies. A network for 1024 number of users with ring-tree topology form using sixteen Optical Add Drop Multiplexers (OADMs) and one hundred forty four star hubs (1x8). Four channels at 193.1 THz center frequency with 100 GHz channel spacing can be added and dropped at each OADM. The signal with 10 Gbps data speed is successfully transmitted up to 150 Km transmission distance. A fault protection scheme for ring topology based passive optical network is also proposed in this chapter.

Finally, chapter 7 covers the summary/conclusions drawn; recommendations and future scope on the basis of results obtained in the third to sixth chapters.

Chapter 3

Architectures of Hybrid (WDM/ TDM) PON

This chapter focuses on the first research objective that is to design and characterize hybrid Passive Optical Network (PON) to improve the efficiency of Optical Network Unit (ONU). Various architectures of hybrid PON system have been proposed to achieve better performance over the previously proposed networks. The proposed systems are analyzed in the terms of Q-factor, Bit Error Rate (BER), optical power, channel spacing, data rate, Carrier to Noise Ratio (CNR), modulation formats etc. In the first architecture, hybrid PON system is proposed for transmission of triple play services (video, voice and data) to various ONUs. Further, bidirectional hybrid PON architecture is presented. A novel cost effective technique i.e. Common Carrier for All Optical Network Units (CCAONUs) is proposed for the hybrid PON with mitigation of non linearity Impact proposed. Finally, four aggressive schemes for energy saving in hybrid PON system are analyzed. This chapter is organized into four sections. In section 3.1, hybrid PON for triple play services is proposed. In section 3.2, bidirectional hybrid PON architecture is reported. Architecture based on CCAONU is presented in section 3.3. Energy efficient passive network is proposed in section 3.4.

3.1 Hybrid PON with Suitable Modulation Format

The demands and expectations of subscribers for high data speed content at long distances motivate the researchers to improve the existing optical networks [87]. Due to huge bandwidth availability, PON can fulfill the requirement of next generation networks [88]. Hybrid Wavelength Division Multiplexing/ Time Division Multiplexing (WDM/ TDM) PON is good postured to be one of the chief ladder in the evolution of access-metro optical networks [89-90]. In recent years, various techniques based PONs like WDM PON [91], TDM PON [92], hybrid (WDM/ TDM) PON [93] have been proven the most promised solution for such networks.

P. J. Urban et al. [94] reported hybrid (WDM/ TDM) PON using Single Mode Fiber (SMF) for transmitting 1.25 Gbps data rate up to 26 Km distance through two wavelength channels. A simple, colorless and polarization independent WDM PON using spectrum sliced technique with SOA has been reported in [29]. 155 Mbps to 1.25 Gbps data rate at 100 GHz channel spacing over 25 Km transmission distance has been successfully

transmitted. Chang-Chia Chi et al. [27] demonstrated TDM PON with different architectures using 1:16 and 1:32 split ratio for 168 ONUs over 10 Km distance. In literature, the proposed architectures are based on transmission of internet data only. We have extended the previous work by making the system capable for transmitting the combination of voice, data and video signals to more number of ONUs. We have proposed a hybrid (WDM/ TDM) PON system accessing triple play services to 128 ONUs. The voice and data signals at 1.25 Gbps speed are transmitted at 1480-1500 nm wavelengths. The video signal at 0.8 Gbps speed is transmitted at 1550–1560 nm wavelengths. The comparative investigation of various data formats for voice and data signals is also done. It has been observed that the most suitable data format for hybrid PON network is Non Return to Zero (NRZ) Rectangular.

3.1.1 System Setup

The block diagram of simulation setup for hybrid passive optical network is shown in figure 3.1. In the proposed system setup 128 users can use triple play services (data, voice and video) up to 28 Km without using any inline amplification. In this system, Central Office (CO) is equipped with Optical Line Terminal (OLT) devices. Optical Network Terminal (ONT) devices are installed at the subscriber end. Fiber distribution is done using a tree-and-branch architecture.

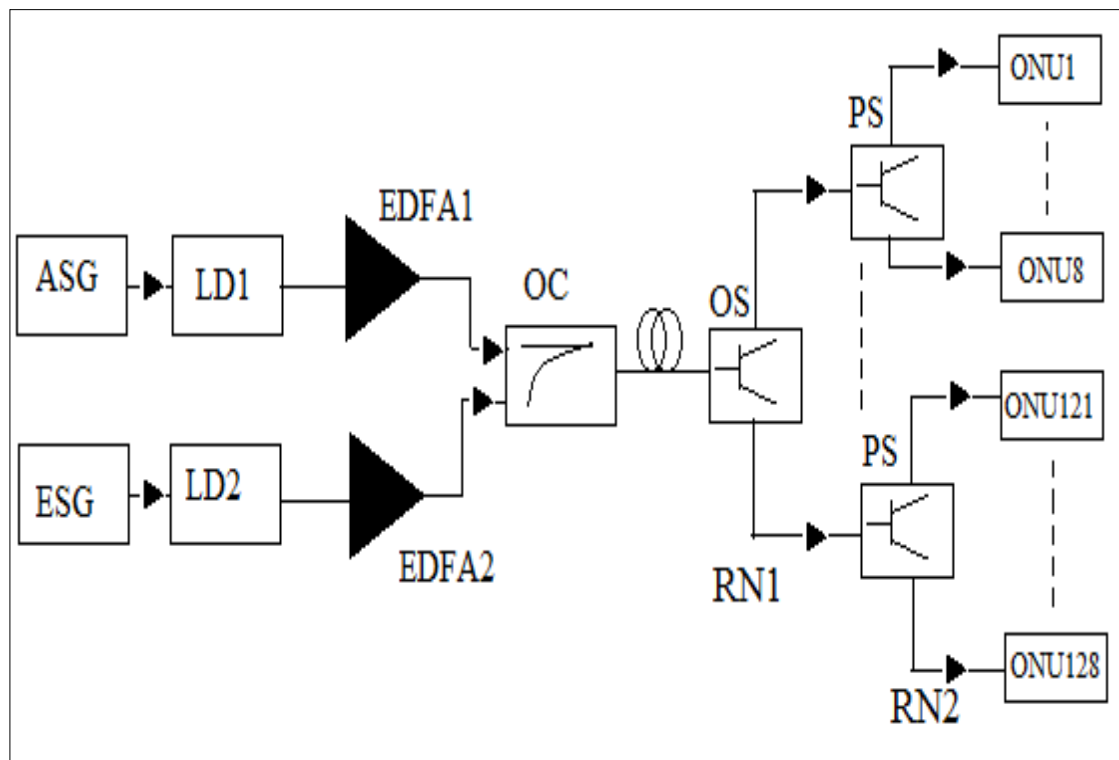


Figure 3.1: Block diagram for hybrid passive optical networks

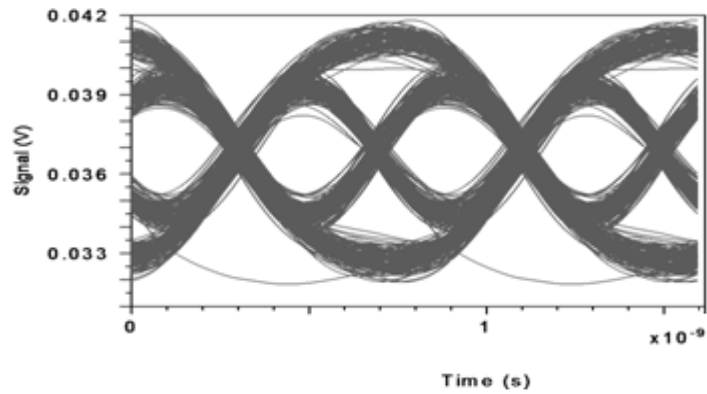
By taking the quick look over different literature, it is evident that the term “triple play” service stands for three services: voice, internet and video. The high speed data components are realized by a downstream signal at 1.25 Gbps data rate. These signals are generated using Electrical Signal Generator (ESG) with Pseudo Random Bit Sequence (PRBS) data generator. The voice components are represented as VoIP (Voice over IP) packet-switched protocol. These signals (Data and Voice) are combined in physical layer simulation and transmitted using RZ/ NRZ or Manchester modulator driver, direct modulated laser and booster amplifier. At direct modulated laser source, the wavelength is kept in the range of 1480-1500 nm for the transmission of these combined signals. The video components are represented as RF SCM (Radio Frequency Sub-Carrier Multiplexed) system with two channels with 55.25 MHz and 547.25 MHz frequencies. Phase Shift Keying (PSK) modulation scheme is used to carry video signals in the channels. These signals are generated using Analog Signal Generator (ASG), summer, direct modulated laser. These signals are transmitted at 1550-1560 nm wavelengths. EDFA pre-amplifier is used to boost up these signals before transmitting. All the signals are further combined using optical combiner and launched into the channel. The signal from the CO is transmitted to the end users through two remote nodes. A fiber link of varying length (10 Km to 35 Km) is installed at first remote node with 1:16 optical splitter. All signals from the optical splitter are passed through another 1 Km fiber with different time delay parameters at second remote node. Each signal is further shared by eight ONUs. The signals have 3-dB pulse width of 5 ps. The second remote node consists of pulse train generator, power splitter and delay blocks. The channel can be accessed by each ONU with 10 ps delay. At the ONU, these signals further demultiplexed into video signals and data/ voice signals. Then, signals are fed to Avalanche Photo Detector (APD) through Fabry Perot filter.

3.1.2 Result and Discussion

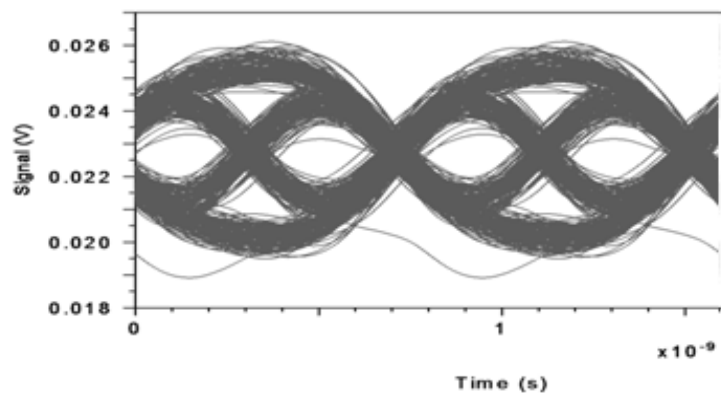
In the proposed hybrid PON system, combined (data, voice and video) signals are transmitted with different modulation formats. The setup is simulated for different modulation formats at different distances. BER and Q factor by varying optical fiber length are calculated. The optical spectrum and eye diagrams are also shown to verify the results.

The figure 3.2 (a, b, c) shows the eye diagrams of hybrid PON system using 128 users with Manchester modulation format at 15, 20 and 28 Km distance respectively. The

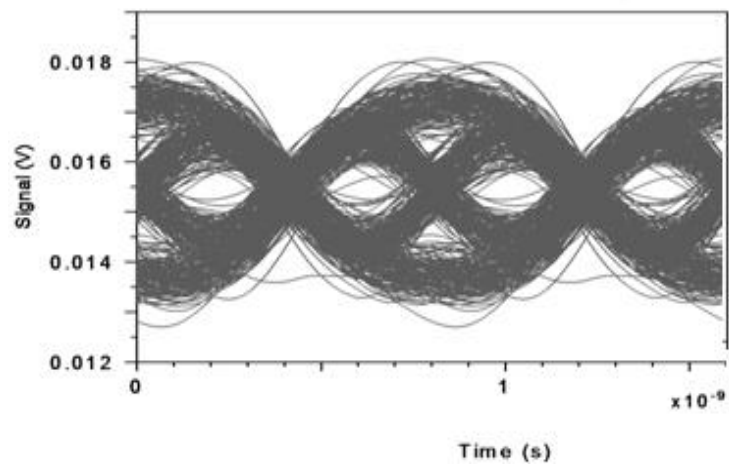
proposed hybrid PON with Manchester Modulation format showed a better performance up to 15 Km. At 20 and 28 Km distances, the eye diagrams are distorted.



(a)



(b)

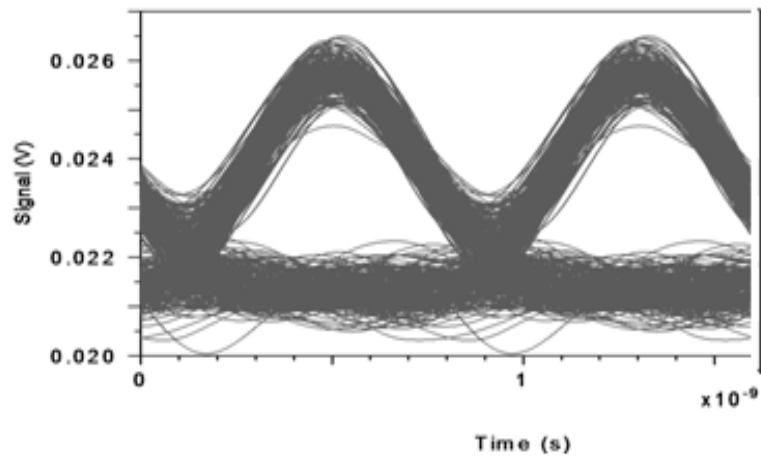


(c)

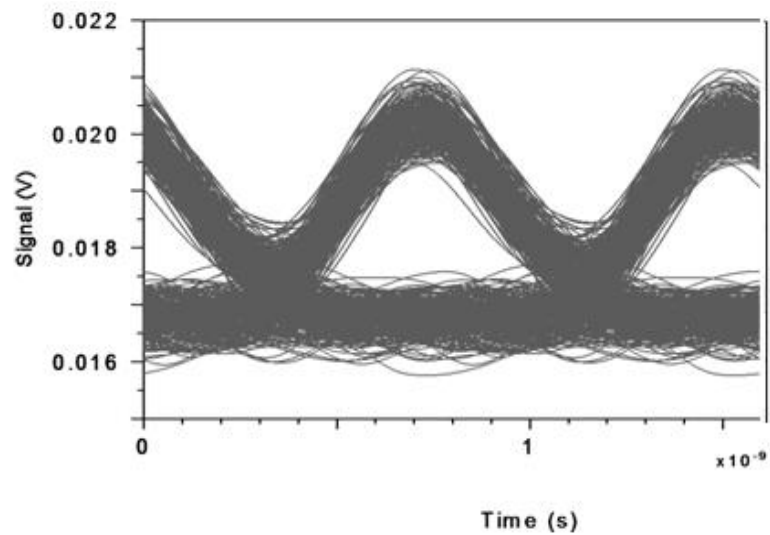
Figure 3.2: Eye diagrams of hybrid PON system using 128 users with Manchester modulation format at (a) 15, (b) 20 and (c) 28 Km distance

The figure 3.3 (a, b, c) shows the eye diagrams of hybrid PON system using 128 users with RZ (Return to Zero) modulation format at 20, 25 and 28 Km distance respectively. It

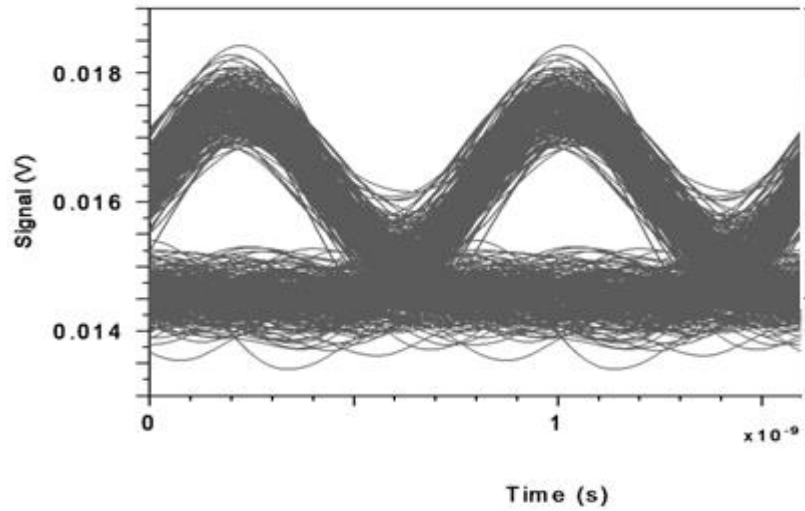
is evident from the eye diagram that the performance of hybrid PON with RZ modulation format can be considered up to 25 Km distance. There is noticeable distortion after this distance. So the users can use these services up to 25 Km. Hence, 128 users can transmit their data, voice and video signals using RZ modulation format up to 25 Km with the best performance.



(a)



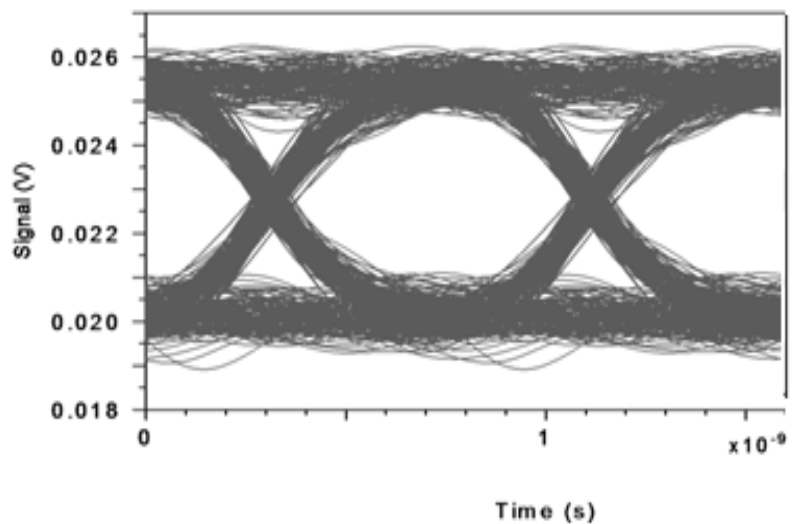
(b)



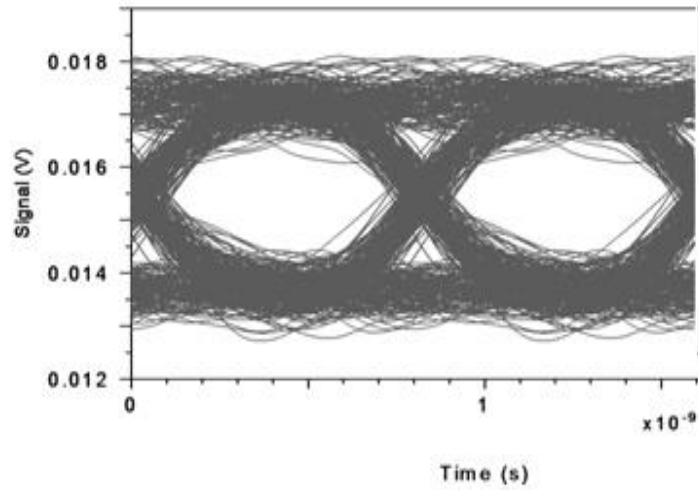
(c)

Figure 3.3: Eye diagrams of hybrid PON system using 128 users with RZ modulation format at (a) 20, (b) 25, (c) 28 Km distance

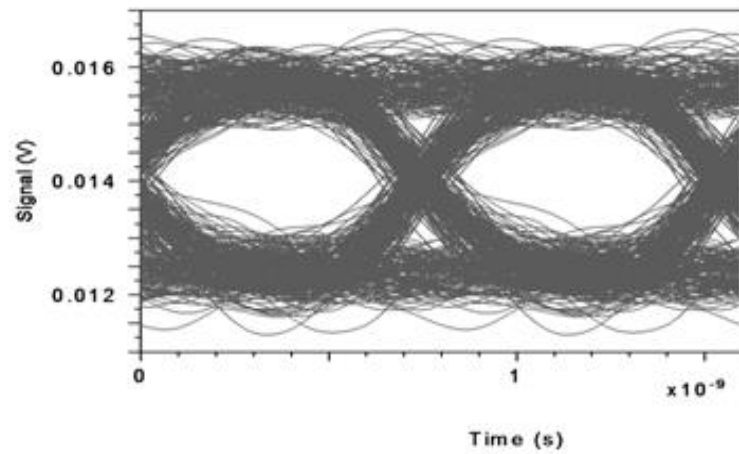
The figure 3.4 (a, b, c) shows the eye diagrams of hybrid passive optical network system using 128 users with NRZ (non return to zero) modulation format at 20, 28 and 30 Km distance respectively. It is evident from the eye diagram that the proposed system with NRZ modulation format showed good eye diagrams at 20 and 28 Km distances. Beyond this i.e. at 30 Km distance, the received eye diagrams are distorted.



(a)



(b)



(c)

Figure 3.4: Eye diagrams of hybrid PON system using 128 users with NRZ modulation format at (a) 20, (b) 28, (c) 30 Km distance

Figure 3.5 shows a BER versus distance for various modulation formats for proposed system using 128 users. The fiber length varies from 10 Km to 34 Km in this figure. It is analyzed that the 128 users can receive the signal up to 19, 25 and 28 Km for Manchester, RZ and NRZ modulation formats with maximum acceptable BER respectively. If we increase the distance, then the BER increases and system is not sufficient to transmit the triple play services. So, the NRZ modulation is best suitable modulation format for triple play services in proposed system.

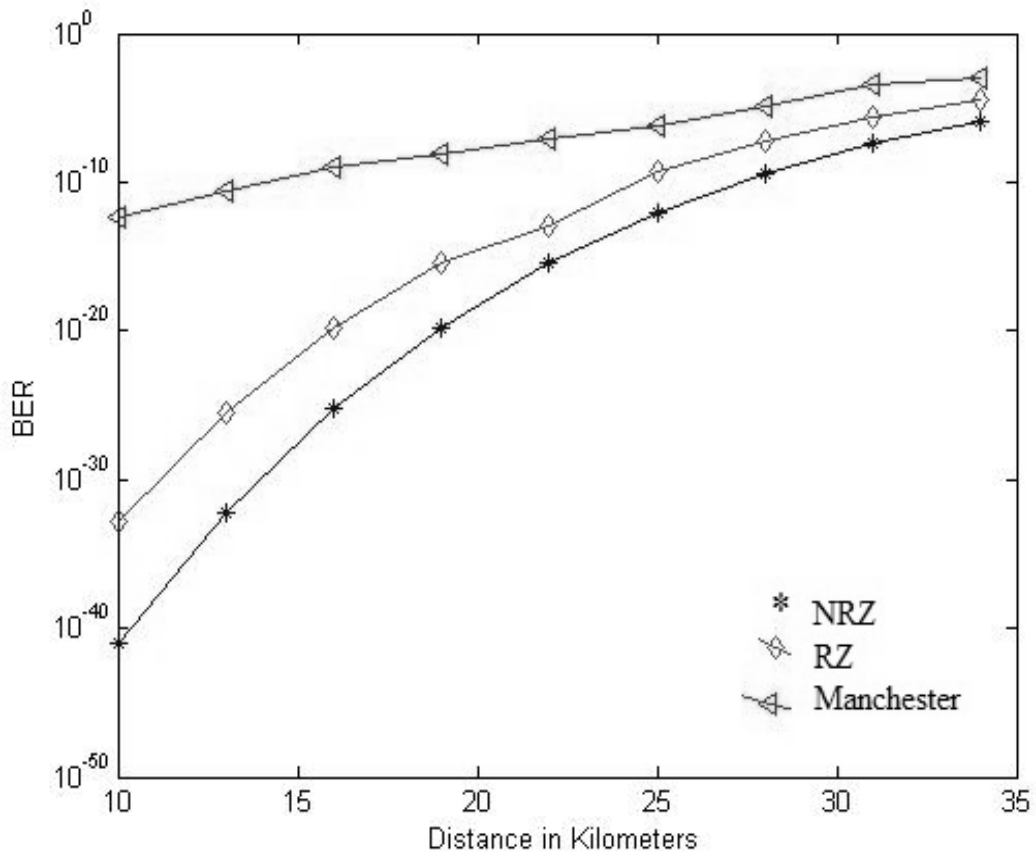


Figure 3.5: BER V/s distance for various modulation formats for hybrid PON system using 128 users

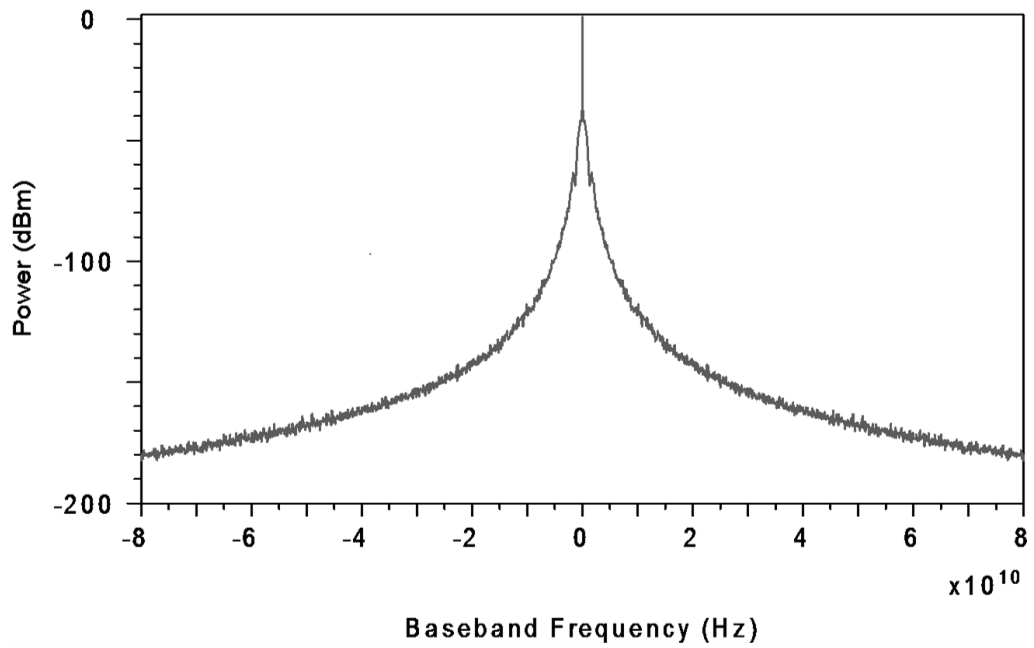


Figure 3.6: Baseband signal spectrum for hybrid PON system using 128 users

Figure 3.6 shows a baseband signal spectrum diagram for hybrid PON system using 128 users. Received output power verses baseband frequency for NRZ modulation format at 28 Km is shown in the figure.

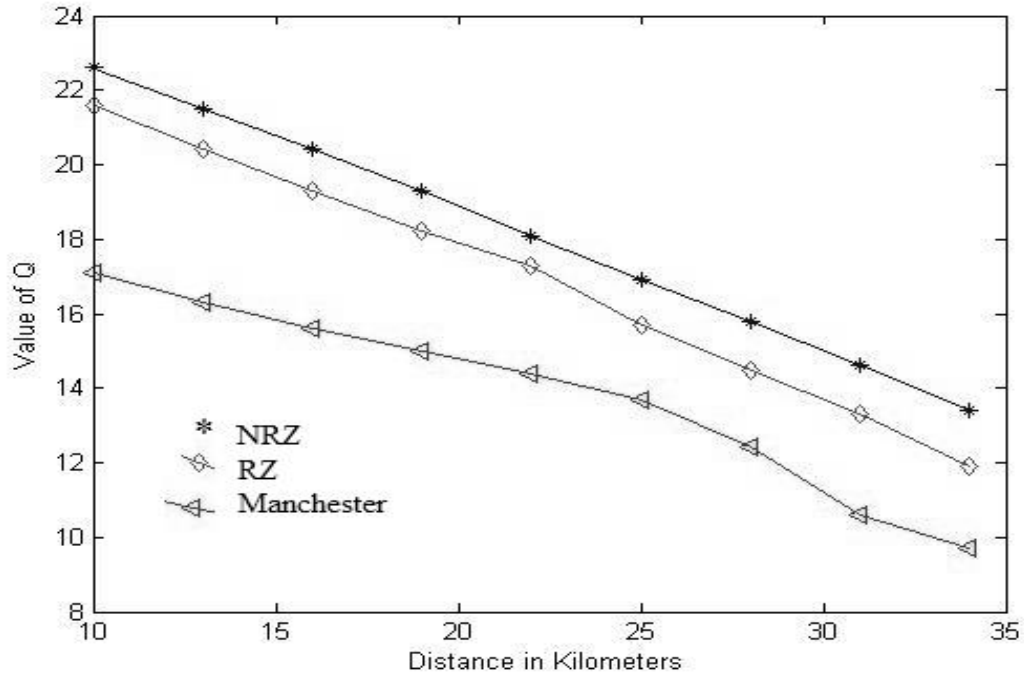


Figure 3.7: The Q factor V/s distance for hybrid PON system using 128 users

Figure 3.7 shows the Q factor V/s distance diagram for hybrid PON system using 128 users. A distance range from 10 Km to 34 Km is considered in this diagram. It is analyzed that the acceptable Q value is achieved up to 19, 25 and 28 Km for Manchester, RZ and NRZ modulation formats respectively with 128 users. If we increase the distance above 28 Km, then the Q value decreases and system is not sufficient to transmit the triple play services. So, the NRZ modulation is best suitable for using triple play services.

3.2 Bidirectional Hybrid (WDM/ TDM) PON

Today the researchers are concentrated on hybrid (WDM/TDM) PON systems to execute the obligation in next-generation of high-bandwidth optical access networks for cost-effective user-shared facilities [91]. This technology is well thought-out to be one of the most promising solutions for the next broadband commitment. In WDM-PONs each user is assigned dedicated channel [88]. The considerable enlargement in today's necessity i.e. demand for audio, internet data, video online, venture connectivity, cloud and data center services etc. can be carried out through this technology [95]. The performance of PONs systems depends upon many parameters like ONU design, amplifiers, lasers, modulators,

effect of non linearity (Cross Phase Modulation (XPM), Four Wave Mixing (FWM) etc.), topology, routing algorithm, location, allocation of wavelengths, capacity planning and cost. Various researchers have described the various optimization techniques based upon these parameters [87].

Fady I. et al. [96] reported a bidirectional SCM–WDM PON using a reflective filter and cyclic AWG. The data rate of 1 Gbps symmetrical for up and downstream was successfully transmitted up to 10 km distance. A bidirectional hybrid wired and wireless access network based on SCM was demonstrated by L. Xu et al. [97]. Single Mode Fiber (SMF) was used to transmit the downstream and upstream signals to 25 Km distance. Chien Hung Yeh et al. [98] presented WDM PON system using re-modulation technique with DPSK. The signal with 10 Gbps data rate was successfully transmitted up to 20 km reach without use of dispersion compensation technique.

In literature, various works on hybrid PON have been reported as shown in table 2.1. Considering [96], a bidirectional SCM–WDM PON using a reflective filter and cyclic AWG was proposed and only 1 Gbps data rate signal for both up and downstream was communicated in 10 km bidirectional optical fiber link. In [97], a bidirectional transmission hybrid wired and wireless access network based on SCM techniques was proposed and demonstrated up to a distance of 25 km only. In [98], 10-Gbps WDM-PON was proposed till 20 km distance only. Till now, we observe that the proposed hybrid PON systems are limited to lesser data rate, a few number of ONU's, up to short distance and comparison of hybrid PON systems for different data rates is not done yet. Most of the papers are based upon downlink transmission only. We extended the previous work by investigating bidirectional hybrid PONs for different data rates at different distances with 128 ONUs.

3.2.1 System Setup

The block diagram of system setup for hybrid PON is shown in figure 3.8. In the proposed model, 128 ONUs can transmit and receive the data with various data rates. The CO is equipped with OLT devices. The transmitter consists of electrical signal generator with PRBS data generator, modulation format coder, laser source and external modulator. The output signals from the transmitter are pre-amplified by a booster EDFA. For realization of bidirectional transmission in single fiber, a circulator with 3 dB insertion loss, 55 dB isolation and -100 dB noise power is inserted to isolate uplink optical signals from downlink.

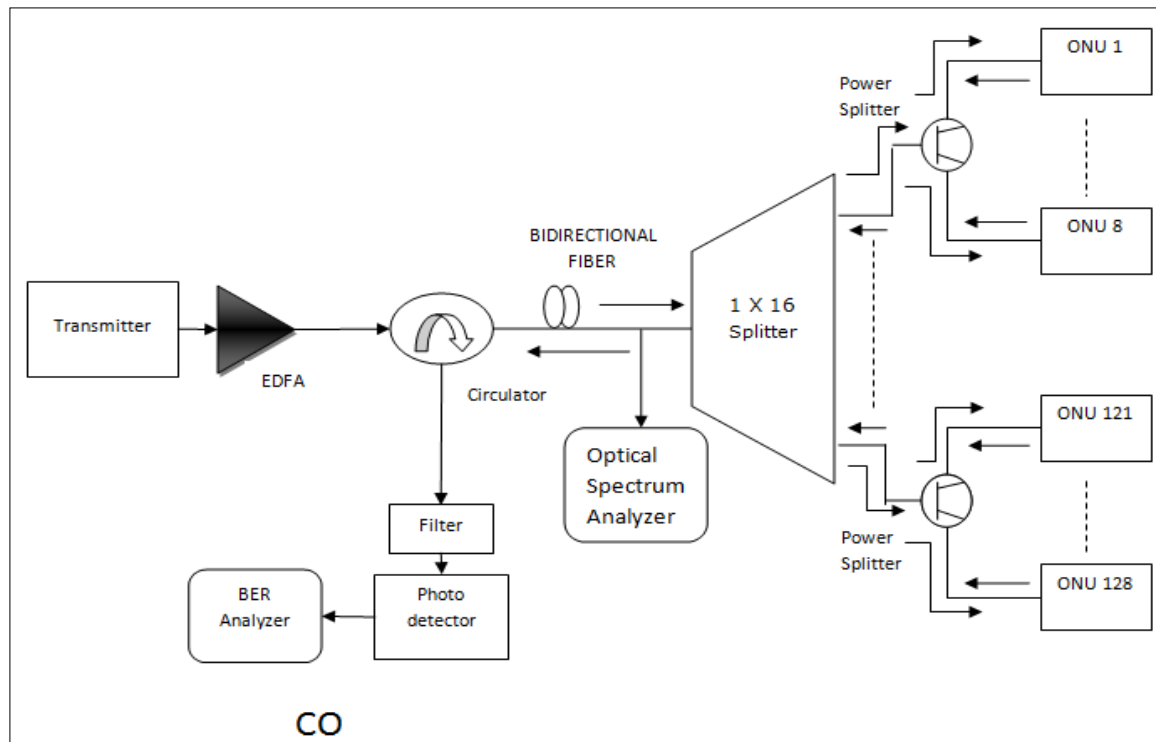


Figure 3.8: Block diagram of system setup for hybrid PON

The internal structure of the transmitter is shown in figure 3.9. PRBS generator is used to realize downstream data link with 1.25, 2.5, 5 and 10 Gbps data rates. NRZ format is used for the input signals. An External Modulated Laser (EML) optical source is used to generate laser beam at 187.1 to 195.8 THz with 100 GHz channel spacing, -3 dBm power and 15 dB extinction ratio. The input signals from data sources are modulated through a carrier (optical signal from the laser source) by using the external Mach-Zehnder modulator.

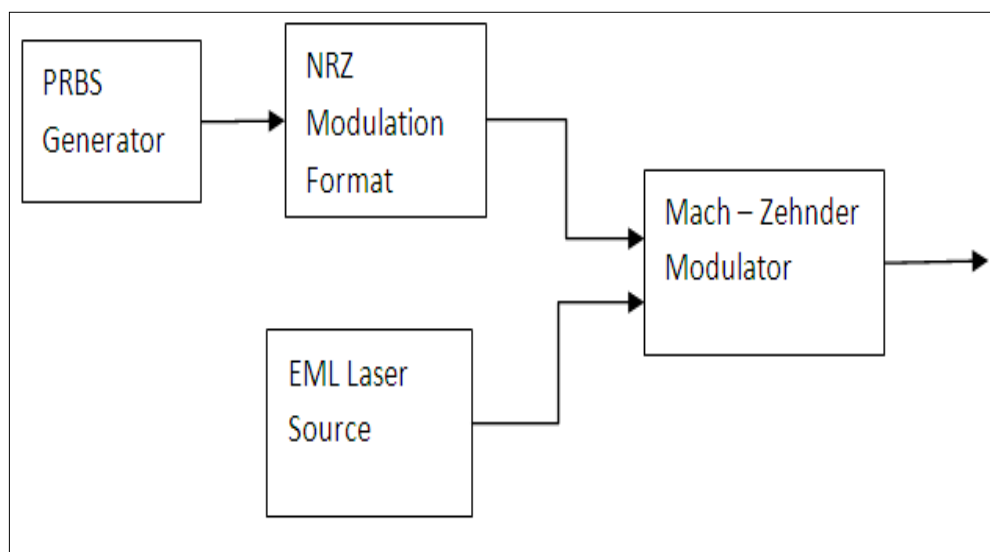


Figure 3.9: Internal Structure of the transmitter

The uplink signals are converted into original signal with the help of Bessel filter and PIN photodiode. The wavelengths assigned to downlink and uplink signals are 1550 nm and 1300 nm respectively. Dispersion Shifted (DS) anomalous fiber distribution with 0.2 dB/km attenuation and 16.75 ps/nm/km dispersion is used in the channel. The input signals from CO are sent through two remote nodes to ONUs. 1:16 optical wavelength splitter is installed at first remote node with a fiber link of varying length. At second remote node (which consists of pulse train generator, power splitter and delay blocks), 1: 8 power splitter is used to feed these signals to eight individual ONUs with different time delay parameters. 10 ps time delay is given to each ONU to receive the signal i.e. the first ONU will receive the signal with zero time delay and the second ONU will receive after 10 ps delay and so on. The block diagram of ONU is shown in figure 3.10.

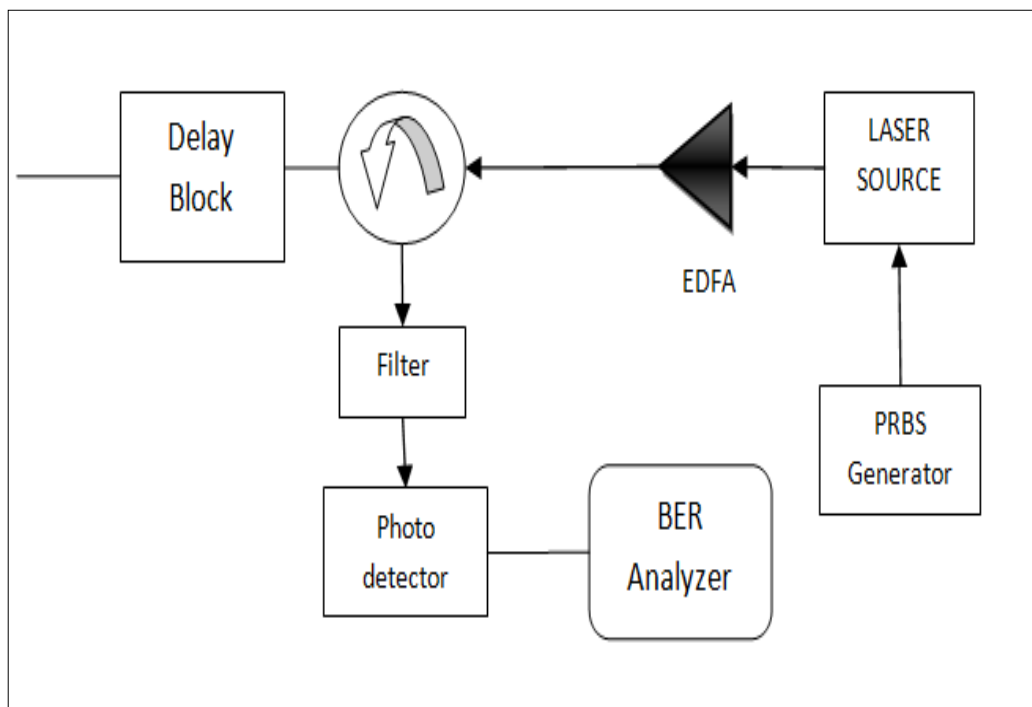


Figure 3.10: Block diagram of ONU

At the ONU, the downlink signals are converted into original signal with the help of Bessel filters and PIN photodiode with 1 A/w response and 10 nA dark current. Different measurement components to analyze the results are also connected to the detector. For the uplink data, PRBS generator is used with EML optical source with 100 GHz channel spacing, -3 dBm power and 12 dB extinction ratio. The proposed system is designed for 128 subscribers with different data rates at various distances. BER and Q factor are most commonly used performance parameters. The Q factor can be defined as [87]:

$$Q = \frac{m_1 - m_0}{\sigma_1 - \sigma_0} \quad \text{---- (3.1)}$$

Where $m_1, m_0, \sigma_1, \sigma_0$ are the mean and standard deviations of the received signal at the sampling instant when a logical 1 and 0 is transmitted respectively.

BER is measure of the probability that an error will occur in a given bit period. It can be estimated by the following inverting formula [87]:

$$\text{BER} = \frac{1}{2} \text{erfc} \frac{Q}{\sqrt{2}} \quad \text{----- (3.2)}$$

In the system setup, a series of signals are received as upstream signals at the OLT side. So, we measured BER individually with the respective ONU.

3.2.2 Result and Discussion

In order to observe the performance of hybrid PON system, the setup is simulated for different data rates at different distances. Various result parameters like BER, Q factor and eye closure at different data rates with respect to optical fiber length for uplink and downlink are observed.

BER versus transmission distance at 1.25, 2.5, 5 and 10 Gbps data rates for downlink graph is shown in figure 3.11.

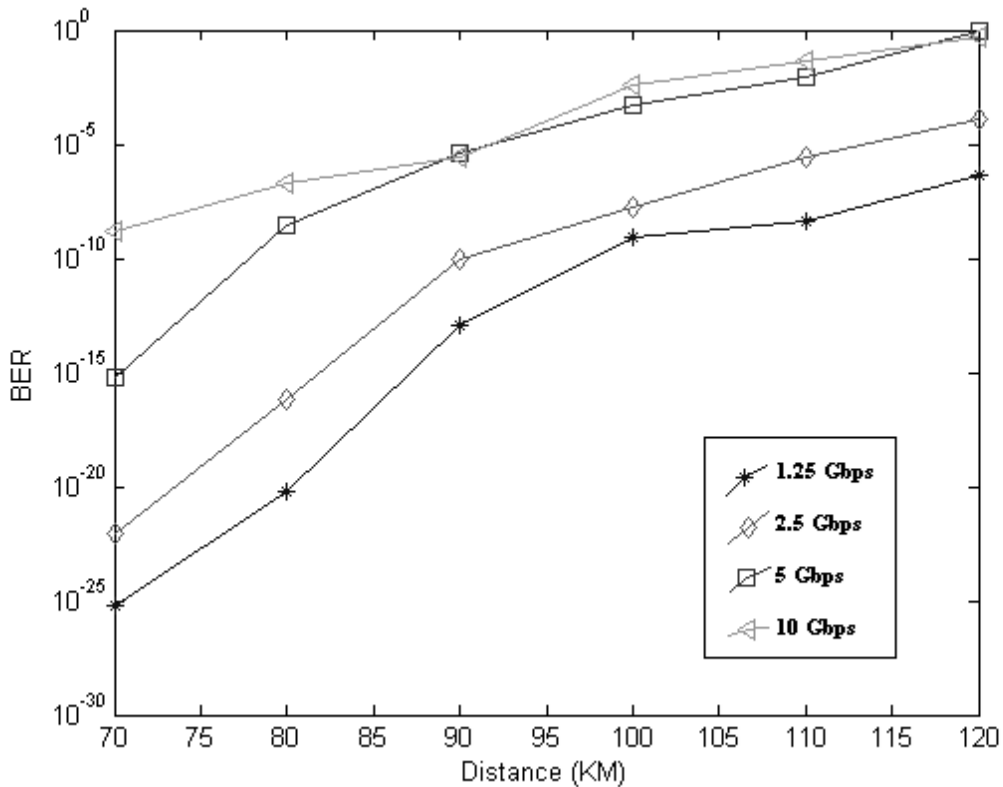


Figure 3.11: BER versus transmission distance at different data rates for downlink

As shown in the figure, BER increases with respect to the transmission distance. The distance ranges from 70 Km to 120 Km in this graph. The most acceptable bit error rate is provided by 1.25 Gbps is 3.8×10^{-9} at 118 Km, by 2.5 Gbps is 1.9×10^{-8} at 102 Km, by 5 Gbps is 2.6×10^{-9} at 80 Km and by 10 Gbps is 1.4×10^{-9} at 73 Km. If we further increase the fiber link length, then BER crosses the minimum acceptable limit and hence system is not suitable to transmit the data.

The graphical representation of Q factor versus transmission distance at 1.25, 2.5, 5 and 10 Gbps data rates for downlink graph is shown in figure 3.12. As we increase the distance, the Q-factor gets decreased due to the fibre non-linearity [87].

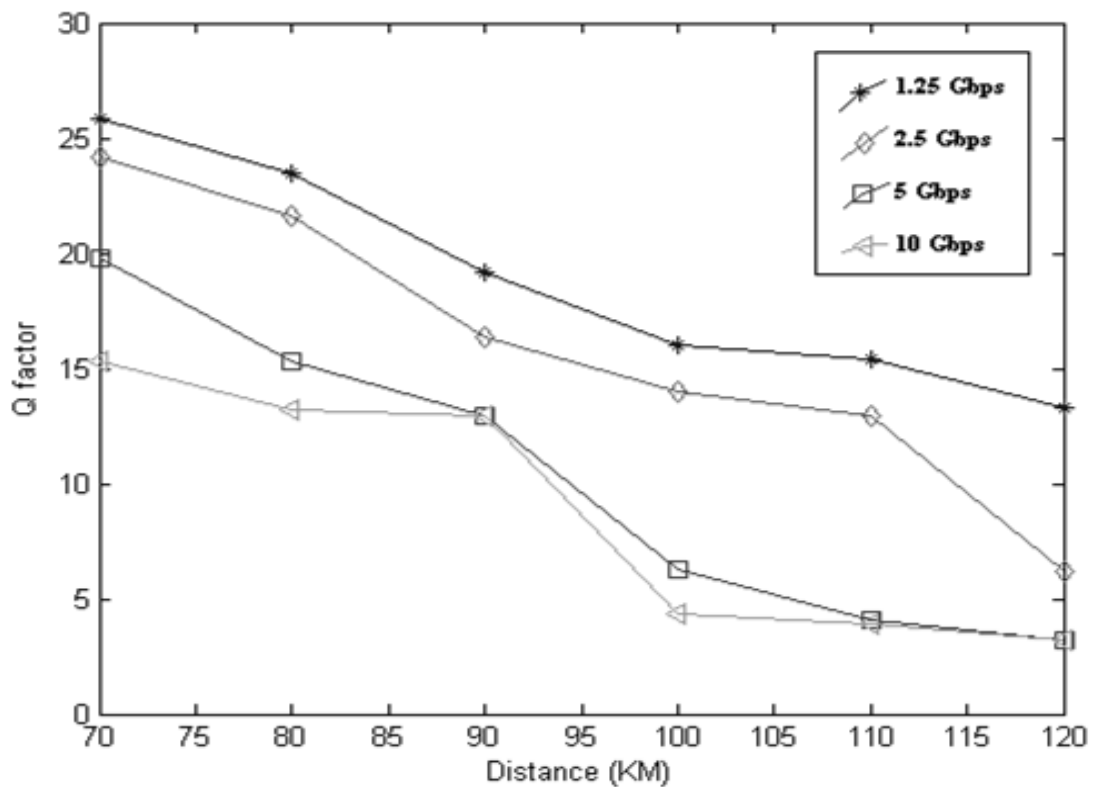


Figure 3.12: Q factor versus transmission distance at different data rates for downlink

It is observed that the Q factor of 15 dB at 110 Km by 1.25 Gbps, 16.4 dB at 90 Km by 2.5 Gbps, 15.3 dB at 80 Km by 5 Gbps and 15.1 dB at 70 Km by 10 Gbps is achieved with 128 users. If we increased the fiber link length above these distance, then the Q factor decreases and hence system is not suitable to transmit the data.

The optical output power of -22, -24, -29 and -33 dBm for downlink and -28, -36, -42 and -48 dBm for uplink are observed for 1.25, 2.5, 5 and 10 Gbps data rates respectively. We observed that the output power received is not same for all the channels while keeping the same or more than 15 dB Q-factor for both uplink and downlink.

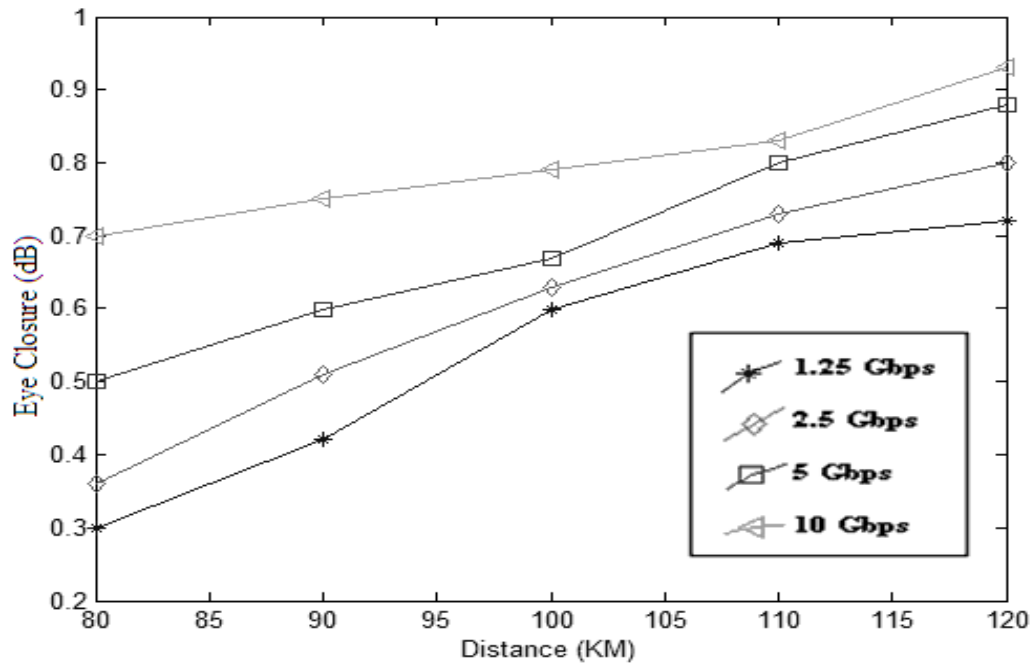


Figure 3.13: Eye Closure for HPON at 1.25, 2.5, 5 and 10 Gbps data rates for downlink

The graphical representation of eye closure versus transmission distance at different data rates for downlink graph is shown in figure 3.13. An eye closure of 0.6542 dB at 115 Km by 1.25 Gbps, 0.6109 dB at 95 Km by 2.5 Gbps, 0.5786 dB at 90 Km by 5 Gbps and 0.7 dB at 80 Km by 10 Gbps data rates is observed. As we increase the distance, the closure of eye is also increased due to the fibre non-linearity like XPM and FWM etc. [87].

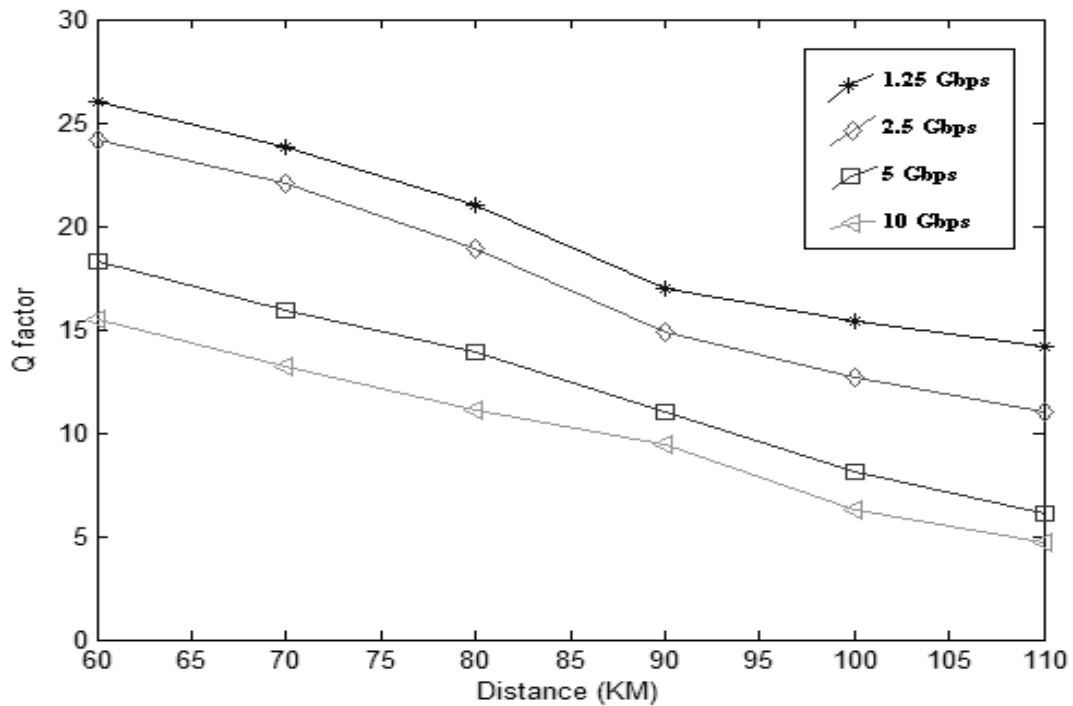


Figure 3.14: Q factor versus transmission distance at different data rates for uplink

The graphical representation of Q-factor versus transmission distance at 1.25, 2.5, 5 and 10 Gbps data rates for uplink graph is shown in figure 3.14. As we increase the distance, the Q-factor gets decreased due to the fibre non-linearity.

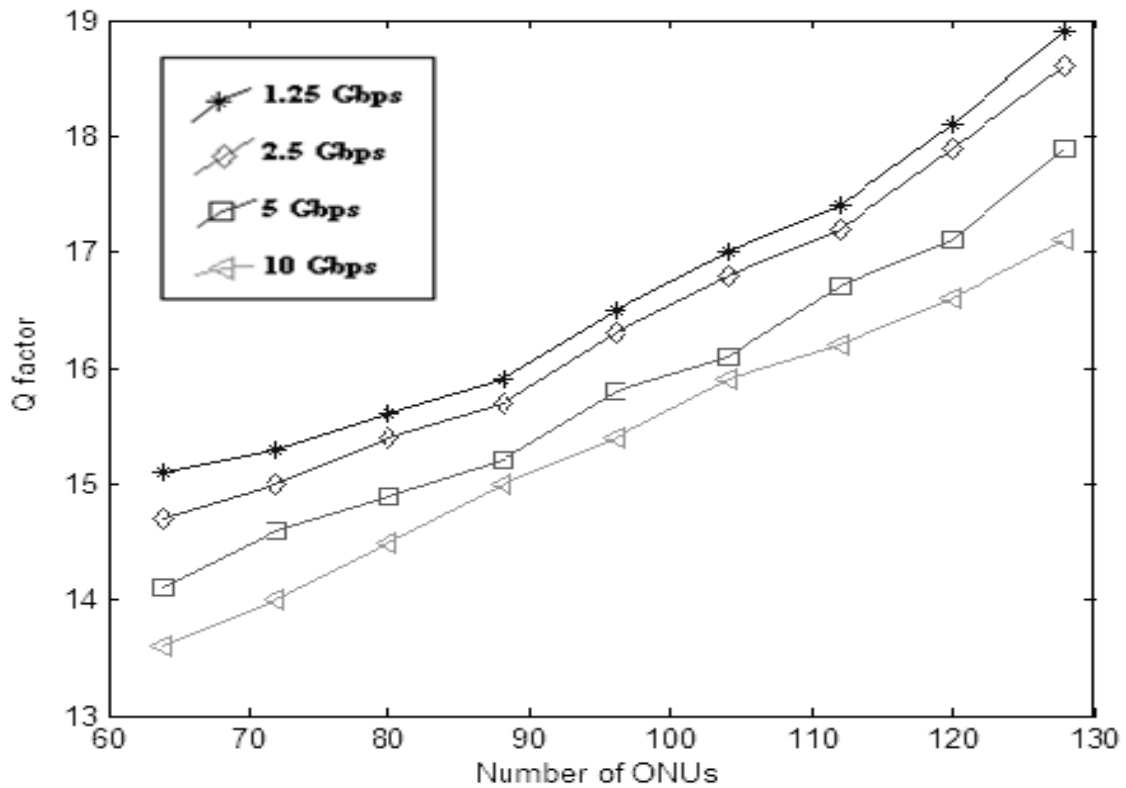


Figure 3.15: Q factor versus number of ONUs at 110 Km for different data rates

The graphical representation of Q value versus number of ONUs at 110 Km for 1.25, 2.5, 5 and 10 Gbps data rates for downlink signal is shown in figure 3.15. It is observed that the Q factor of 15.1 dB at 1.25 Gbps, 14.7 dB at 2.5 Gbps, 14.1 dB at 5 Gbps and 13.6 dB at 10 Gbps data rate is achieved for 128 ONUs at 110 Km transmission distance.

3.3 HPON using Cost Effective CCAONUs technique

Today the researchers are giving more focus on developing of new access network architectures to support high data rate with larger bandwidth for the future applications [90]. PONs are considered as a promising solution to provide a cost-effective, highly flexible and scalable network for all the end subscribers [85]. In [99], four directly modulated injection locked FP-LDs with 2.5 Gbps data rate were used to distribute the carriers at a transmission distance of 25 Km through SMF. In [66], the proposed network was experimentally analyzed over 60-Km fiber at 622 Mbit/s only. In [95], a hybrid PON with DFB laser and FBG is proposed for 2.5 Gb/s data rate up to 15 Km distance only. A

hybrid PON for 32 channels consisting of 2.5 Gbps data rate with RSOA over 50 Km is proposed in [52].

In literature, the advancements in passive optical networks have been reported. We observed various proposed ONUs are very complex and costly due to requirement of optical sources for generation of the carriers. Also, the data rate and total number of ONUs are very less. In this section, we have proposed a hybrid PON with 256 number of ONUs for 10 Gbps data rate up to 190 Km transmission distance with keeping the circuit simple and cost effective. The main advantage of this network is the use of CCAONUs technique which reduces the overall cost of the network abruptly. In this technique, an extra carrier is generated at CO with downstream carrier to re-modulate it for upstream transmission at the subscriber end. This makes ONU very simple and cost effective. So, there is no requirement of generation of carrier at the ONU end. In this way, using the extra carrier at OLT, we have reduced the numbers of laser sources equal to the number of ONUs. For the proposed system, we have reduced 255 numbers of laser sources. Moreover, the system is also investigated to mitigate the impact of non linearity like Rayleigh Scattering (RS) and Stimulated Brillouin Scattering (SBS).

3.3.1 System Setup

The block diagram of system setup for bidirectional hybrid PON is shown in figure 3.16. In the proposed model, the CO is equipped with WDM Transmitter and Semiconductor Optical Amplifier (SOA) with 6 dB gain.

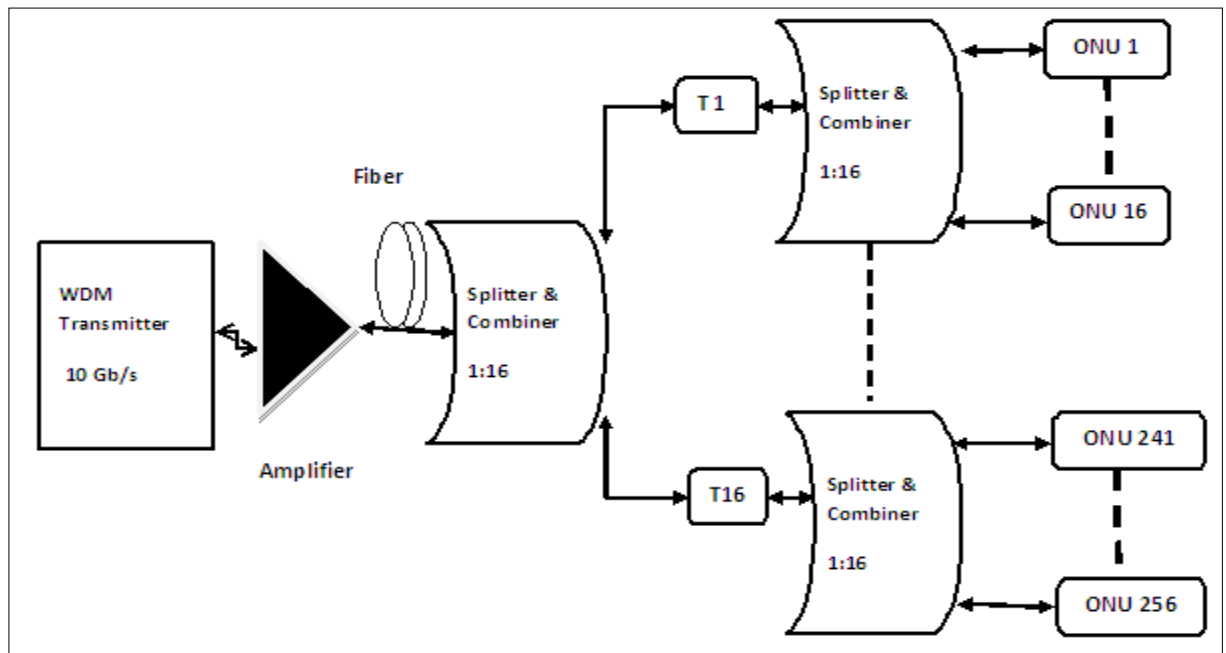


Figure 3.16: Block diagram of system setup for hybrid PON

A bidirectional fiber link (with 0.2 dB/Km attenuation and 16.75 ps/nm/Km dispersion) of varying length is employed to communicate between CO and subscriber's end. The optical signals from fibers are sent through two remote nodes. 1x16 passive splitter and combiner (with coupling factor of 0.50) is used at first remote node and data is further divided to 256 ONUs using sixteen 1x16 splitters and combiners with 10 ps time delay. WDM transmitter consists of three sections viz. carrier for upstream, carrier for downstream and reception of upstream data. To generate carrier for upstream data, CW laser source (with 1310 nm wavelength and 100 MHz line width) and electrical signal generator are used and data is modulated with Mach-Zehnder modulator (with 30 dB extinction ratio). For downstream signal at 10 Gbps data rate, PRBS data generator is used. The signal is further coded in NRZ modulation format.

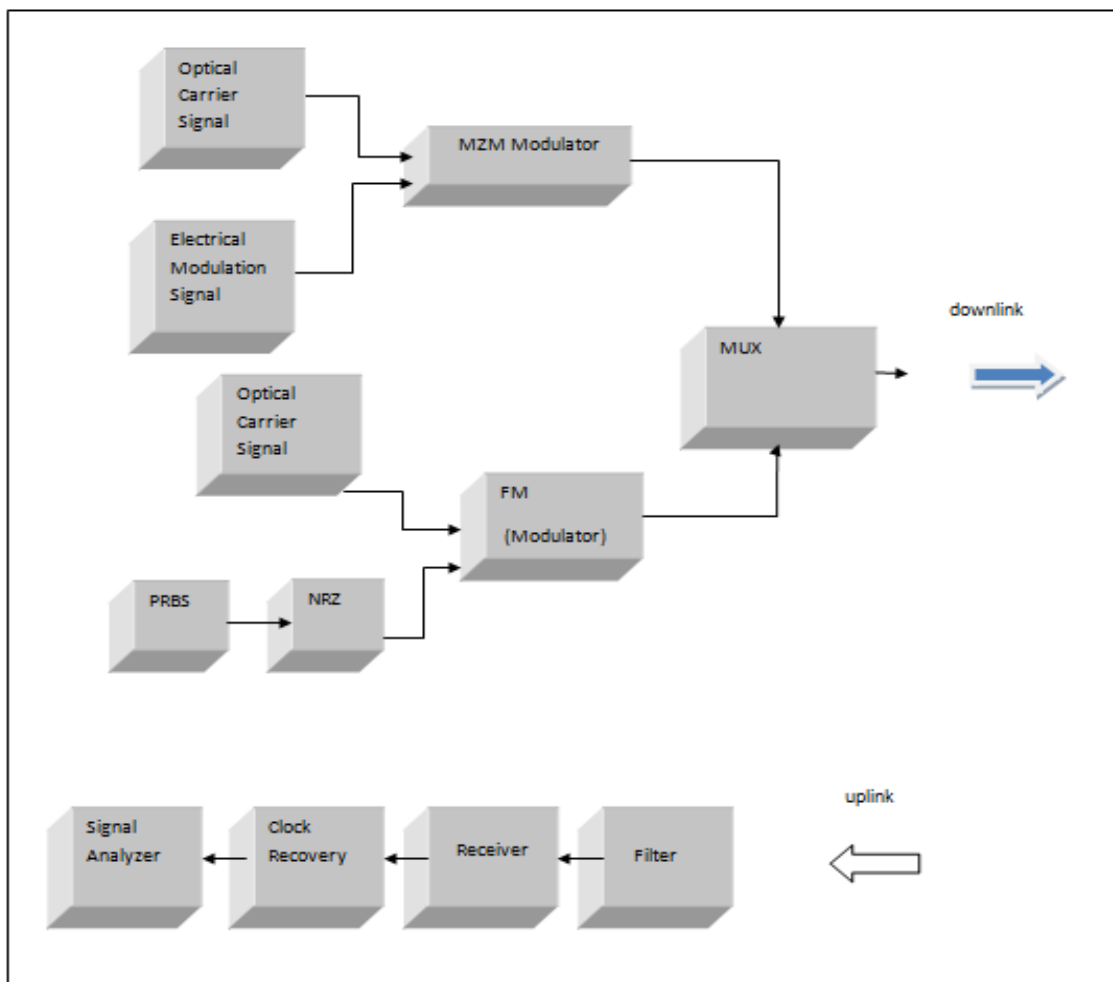


Figure 3.17: The internal structure of OLT

The signals from data source and CW laser tuned at 1550 nm are fed to the FM modulator. This modulator is operated at high frequency optical carrier signal with 10.0e9

Hz frequency. An arbitrary polarization state is used for the input optical signal so that the output polarization is the same as the input signal after FM modulator. The output power (P_{out}) of this modulator can be defined as

$$P_{out}(t) = P_{in}(t) \cdot \exp(j 2 \pi \int \Delta f \cdot I(\tau) d\tau) \quad \text{---- (3.3)}$$

Where P_{in} denotes the input power, Δf is the frequency deviation and $I(\tau)$ is electrical modulation signal. The output signals are sent to channel using 2x1 multiplexer (with 3 dB insertion loss). The internal structure of OLT is shown in figure 3.17. The uplink signals are recovered with the help of Bessel filter and On-Off Keying (OOK) receiver which used PIN photodiode (with 1A/W responsivity, zero ampere dark current, thermal noise of 10^{-11} A/ $\sqrt{\text{Hz}}$) is used the optical signal to convert into the electrical signal. Signal analyzer and clock recovery module are used to observe the results.

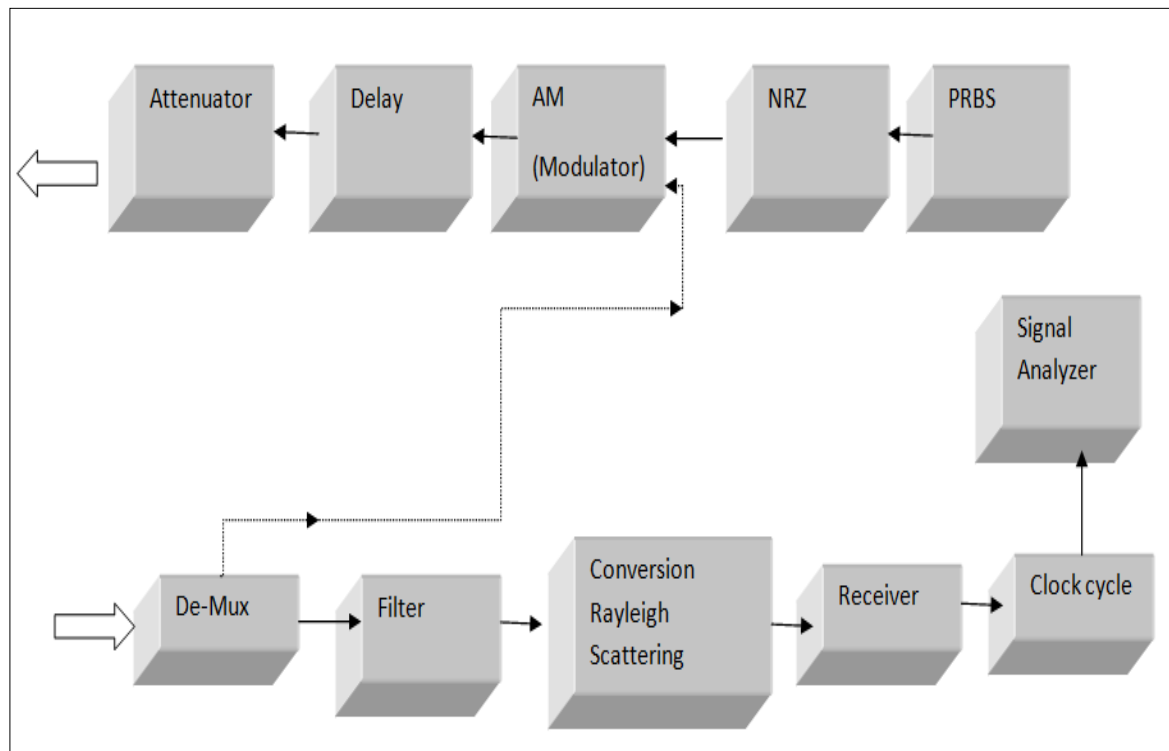


Figure 3.18: Block diagram of ONU

The block diagram of ONU is shown in figure 3.18. The signal is passed through 1x2 De-multiplexer. The downstream signal is recovered by Bessel filter and phase converter module. The impact of non linearity like RS and SBS is mitigated using phase modulating technique in this module. All distorted signals of the same frequency, phase and power are combined into one signal. The resultant signal is sent to a threshold device (Conversion Rayleigh Scattering Model) where a threshold level is defined on the basis of

the centre frequency of these signals so that these distortions can be mitigated. The SBS frequency shift value is quantized to $1/T_b$ frequency grid. The backscattered parameter has been kept linear proportionally to the reflected power per meter. Then signal is fed to OOK receiver which converts received optical signal into electrical signal. To generate upstream data, PRBS is used with 10 Gbps data rate and NRZ modulation format. The signal from de-multiplexer is used as carrier signal and data is modulated using AM modulator for upstream. This modulator is associated with the electrical modulation signal into the logical channel. Unit modulation index is used for the modulator. The output power (P_{out}) of this modulator can be defined as

$$P_{out}(t) = P_{in}(t) \cdot \int ((1-m) + m \cdot I(\tau)) d\tau \quad \text{---(3.4)}$$

Where P_{in} denotes the input power, m is the modulation index and $I(\tau)$ is electrical modulation signal. At the ONU side, we are not using any laser source but the carrier is remodulated via extra carrier generated at the CO. This technique implies that a common carrier, generated at OLT for all ONUs, makes the ONU very simple and cost effective.

3.3.2 Result and Discussion

In order to observe the performance of proposed hybrid PON system, the setup is simulated (in VPI Transmission maker 8.7 software) under different types of non linear crosstalk effects with 256 ONUs. Q factor verses distance with 10 Gbps data rate for upstream transmission is shown in figure 3.19.

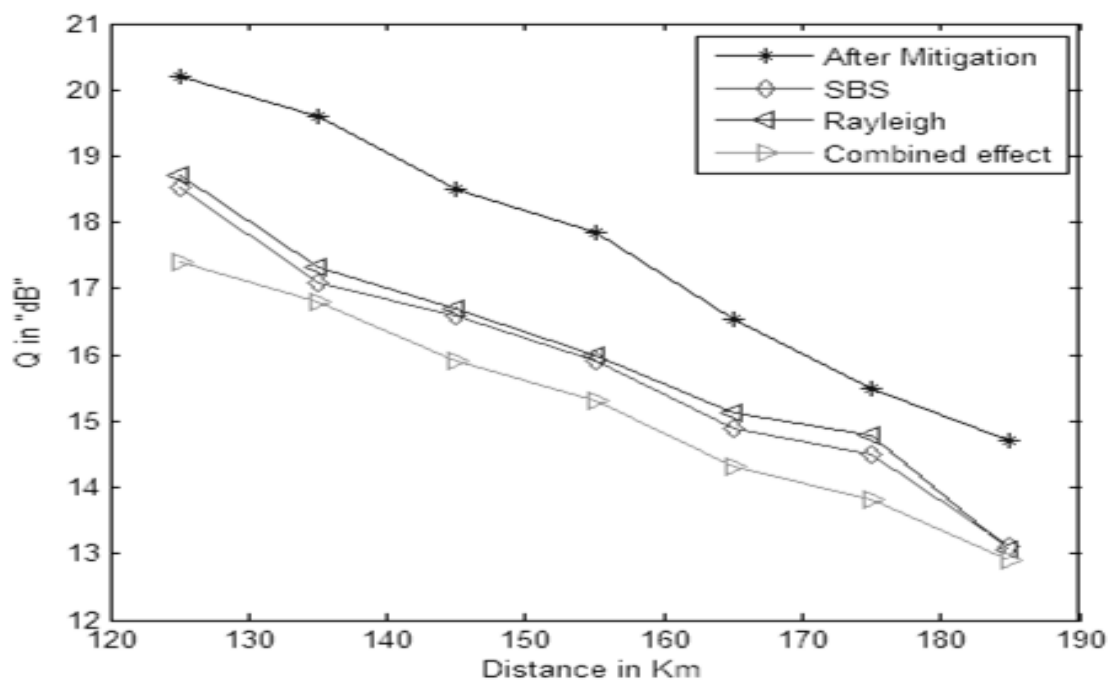


Figure 3.19: Q factor Vs Distance with 256 ONU for upstream at 10 Gbps data rate

As shown in the figure 3.19, Q factor decreases with respect to the transmission distance. The distance of fiber link ranges from 125 Km to 185 Km. It is evident that the Q factor of 14.7, 13.06, 13.1 and 12.96 dB with 256 ONUs and 10 Gbps data rate is observed by various effects such as After Mitigation, SBS only, Rayleigh only and Combined effect of both SBS and RS non linearity at 185 Km distance respectively.

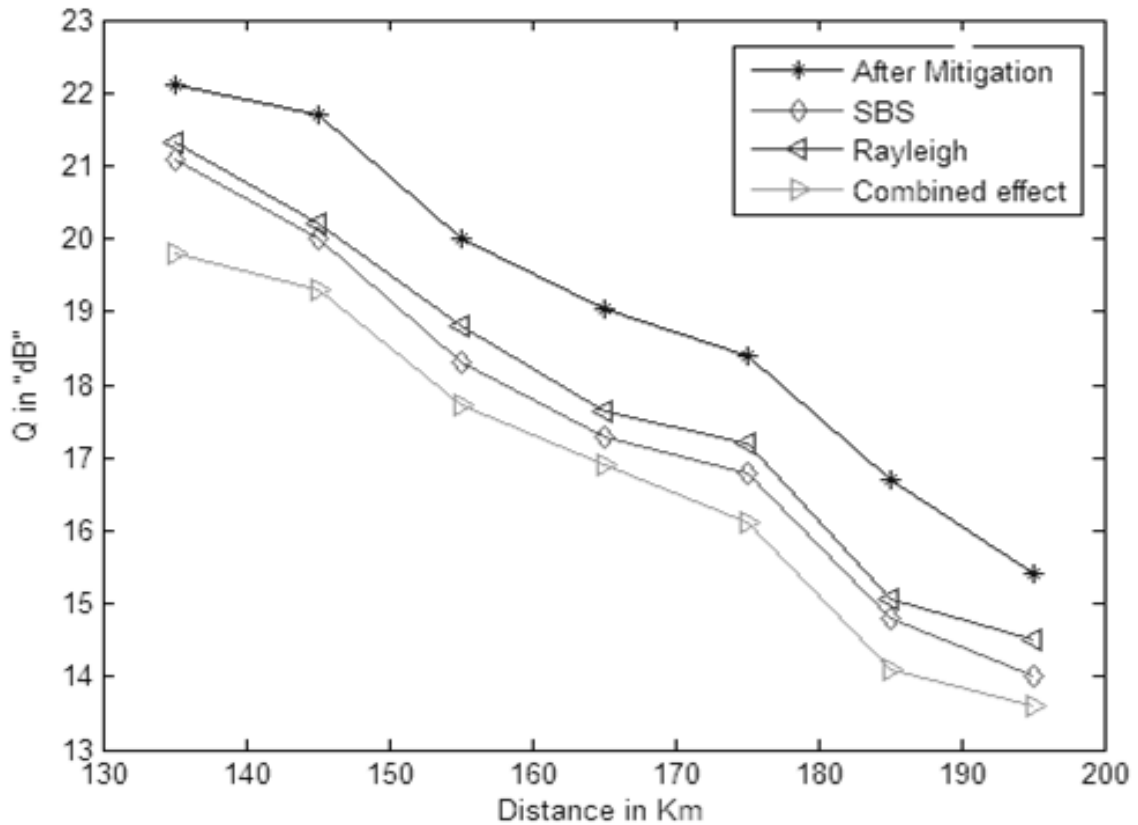


Figure 3.20: Q Vs Distance with 256 ONU for Downlink at 10 Gbps data rate

The graphical representation of Q factor versus transmission distance with 256 ONU for Downstream at 10 Gbps data rate is shown in figure 3.20. The distance of fiber link ranges from 135 Km to 195 Km. It is evident that the Q factor of 15.4, 14.5, 14 and 13.6 dB with 256 ONUs at 10 Gbps data rate is achieved by various effects i.e. After Mitigation, SBS only, Rayleigh only and Combined effect of both SBS and RS non linearity at 195 Km distance respectively.

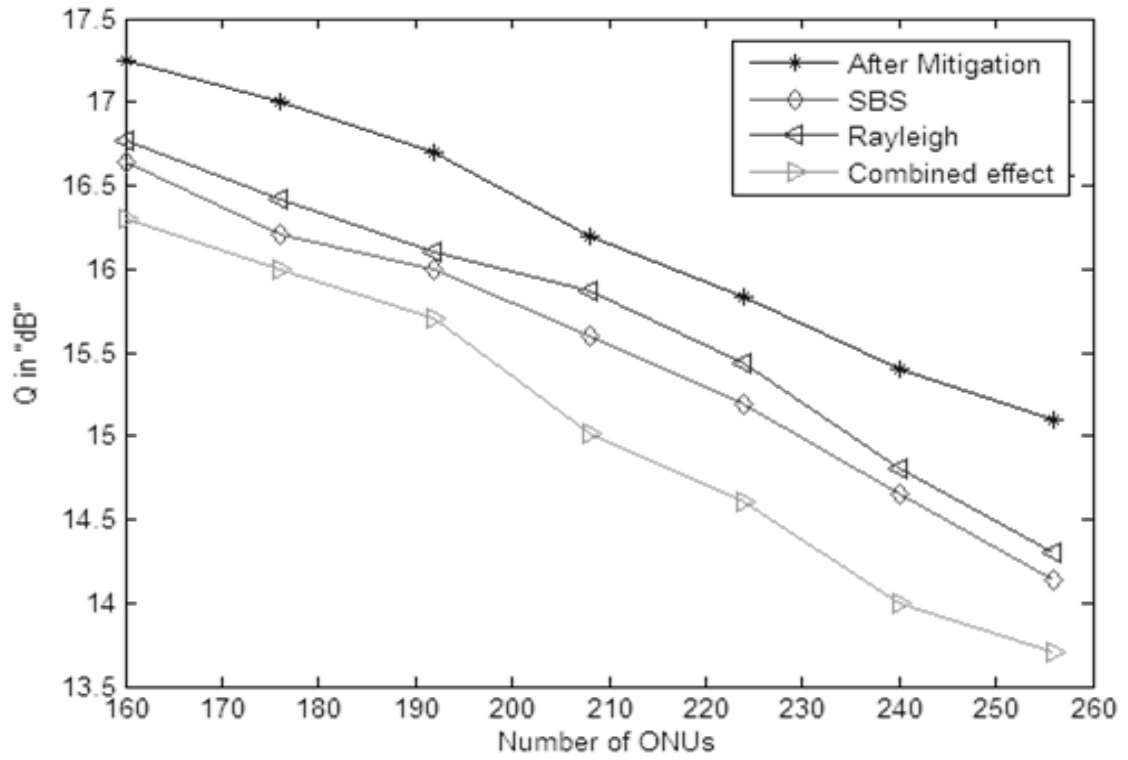


Figure 3.21: Q factor Vs Number of ONUs at 180 Km for upstream with 10 Gbps data rate

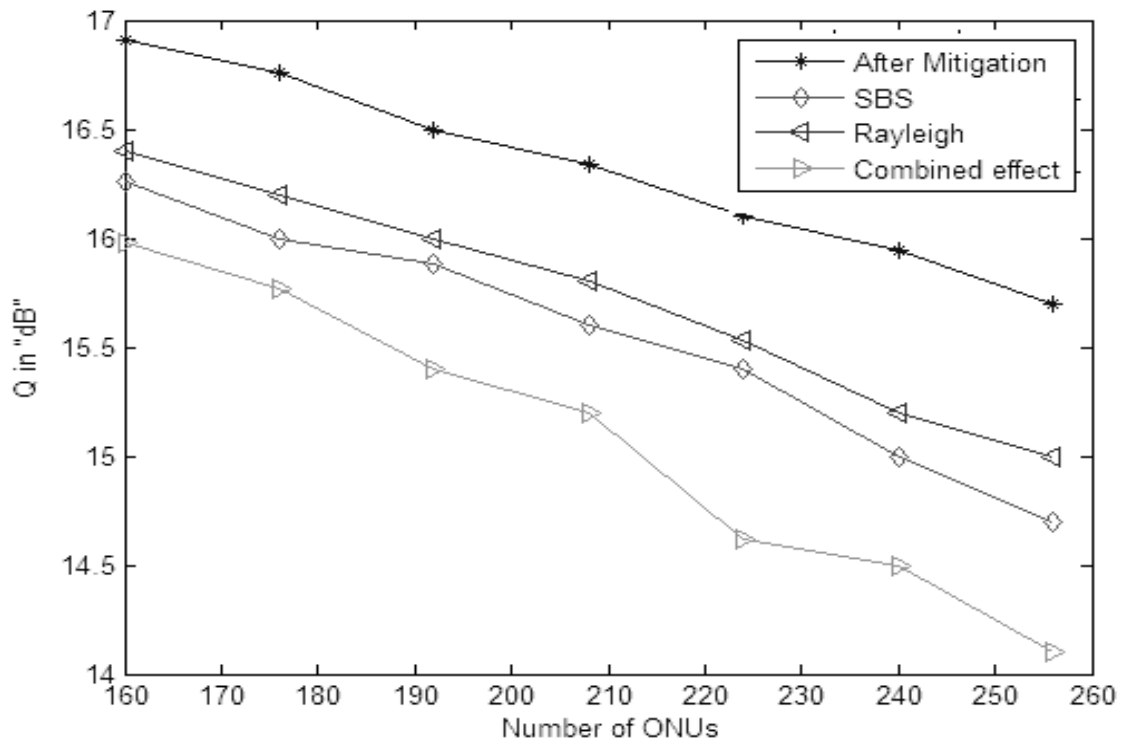


Figure 3.22: Q factor Vs Number of ONUs at 190 Km for downstream with 10 Gbps data rate

The graphical representation of Q factor versus number of ONUs at 180 Km for upstream with 10 Gbps data rate is shown in figure 3.21. The number of ONUs ranges from 160 to 256. It is evident that the Q factor of 15.1, 14.3, 14.14 and 13.71 dB with 256 ONUs at 10 Gbps data rate is achieved by After Mitigation the non linearity, SBS only, Rayleigh only and Combined effect of both SBS and RS non linearity at 180 Km distance respectively. The graphical representation of Q factor versus number of ONUs at 190 Km for downstream with 10 Gbps data rate is shown in figure 3.22. The number of ONUs ranges from 160 to 256. It is evident that the Q factor of 15.7, 15, 14.7 and 14.1 dB with 256 ONUs at 10 Gbps data rate is achieved by After Mitigation the non linearity, SBS only, Rayleigh only and Combined effect of both SBS and RS non linearity at 190 Km distance respectively. The results vary for the downstream and upstream at the same distance or at the same number of ONUs. Because at the ONU end, the re-modulated carrier is used for upstream data, whereas, the data is transmitted with optical carrier directly at the OLT end. Secondly, different wavelengths are used for downstream and upstream.

3.4 Energy Efficient Bidirectional Passive Optical Green Networks

Energy saving and reduction in the emission of carbon dioxide, sulphur etc. have become one of the prime focus for the deployment of next generation networks. Due to less power consuming, PONs are the best promising solution for such networks. Due to the tremendous growth in numbers of users, the networks are deployed with large number of equipments [83]. These equipments consumed high amount of electricity power. This consumption led interest in designing of power efficient green networks for future generation. International Telecommunication Union (ITU) and Institute of Electrical and Electronics Engineers (IEEE) have defined energy efficient Gigabit Passive Optical Networks (G-PON) in 2011 [11] and Ethernet Passive Optical Networks (E-PON) in 2012 [100] respectively with discontinuation transmission instead of continuous mode in conventional transmission system [101]. The energy consumption can be minimized at physical, data link and Medium Access Control (MAC) layers. Small size and low power consumptions devices (optical transmitters, receivers, multiplexers etc.) are proposed at physical layers [102]. At the data link layer, the direct communication between OLT and ONU without consisting any Remote Node (RN) was proposed as solution in [103]. Using devices or function module in sleeping mode is another efficient solution at MAC layer control [101].

In GPON, the receivers consume 40%, the transmitters consume 25%, the MAC layer controls and other devices consume 35% of the total power of the CO. There is more than 3 Watts of leakage power consumption at the ONU with 2 Mb buffer capacities. The power burden adds up with the upgrade in the memory [103]. In this section, we have addressed four aggressive schemes viz. No Buffer (NB), With Buffer (WB), Reduced Buffer (RB) and Reduced Buffer with Small Packet (RBSP) to reduce the leakage power. The reduction of the packet size leads the delay and hence overall degradation in the service. We have also discussed the effects of the packet delay to the network performance.

3.4.1 System Setup

The block diagram of system setup for bidirectional hybrid (WDM/ TDM) PON based on tree topology is shown in figure 3.23. The OLT is equipped with sixteen photonic integrated circuits based TRx array along with a bidirectional optical fiber of 50 Km link. The data is de-multiplexed into sixteen wavelengths of upstream and downstream. Each wavelength is passed through AWG router at remote node. The signal is further splitted to 128 ONUs using 1x8 power splitter and combiner with 10 ps time delay.

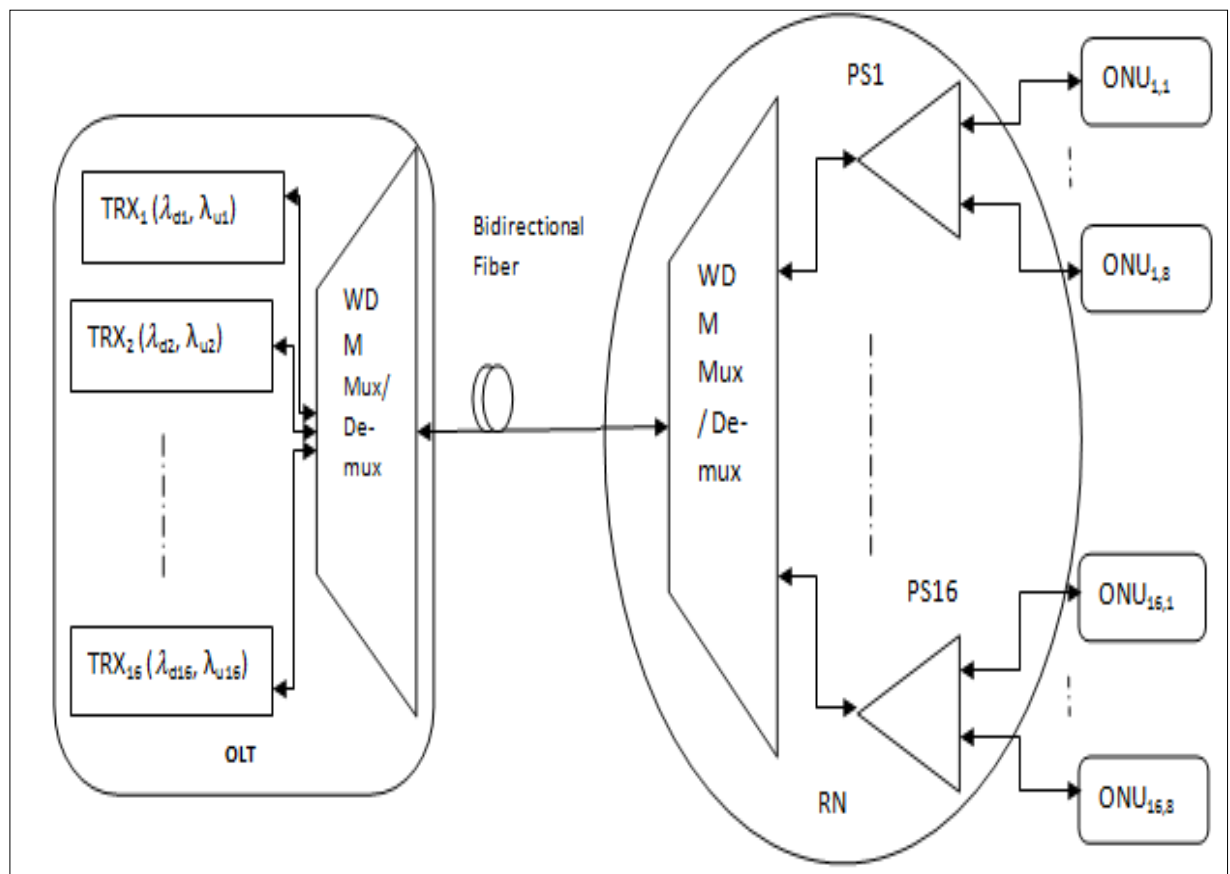
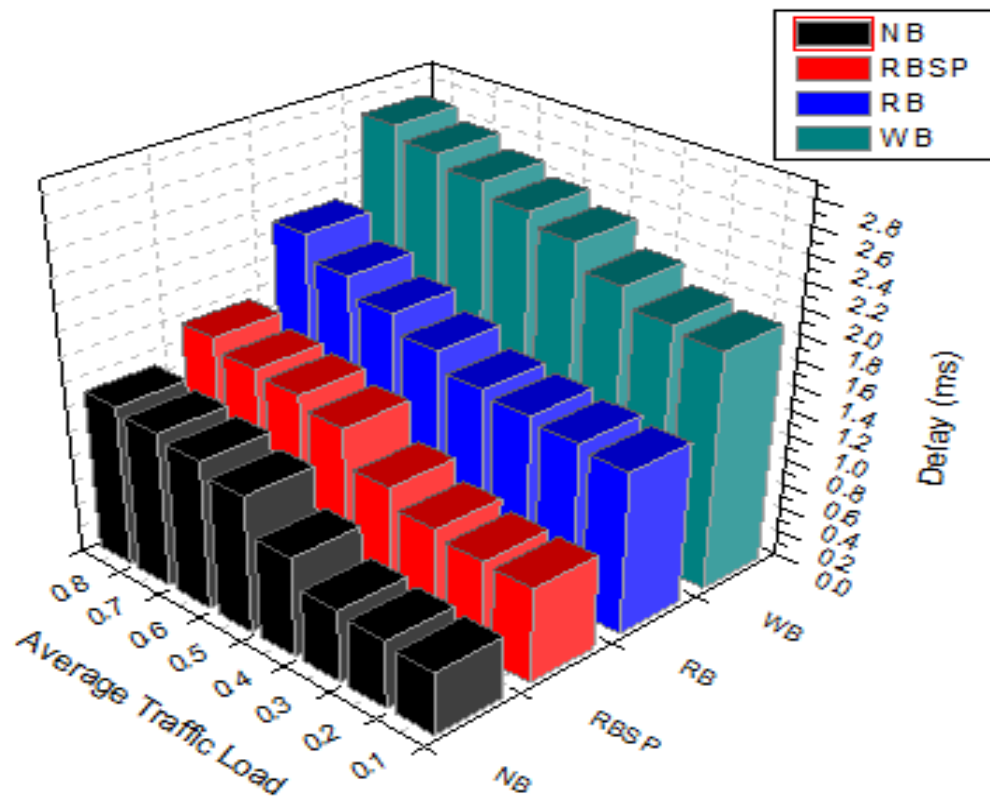


Figure 3.23: Block diagram of system setup for hybrid PON

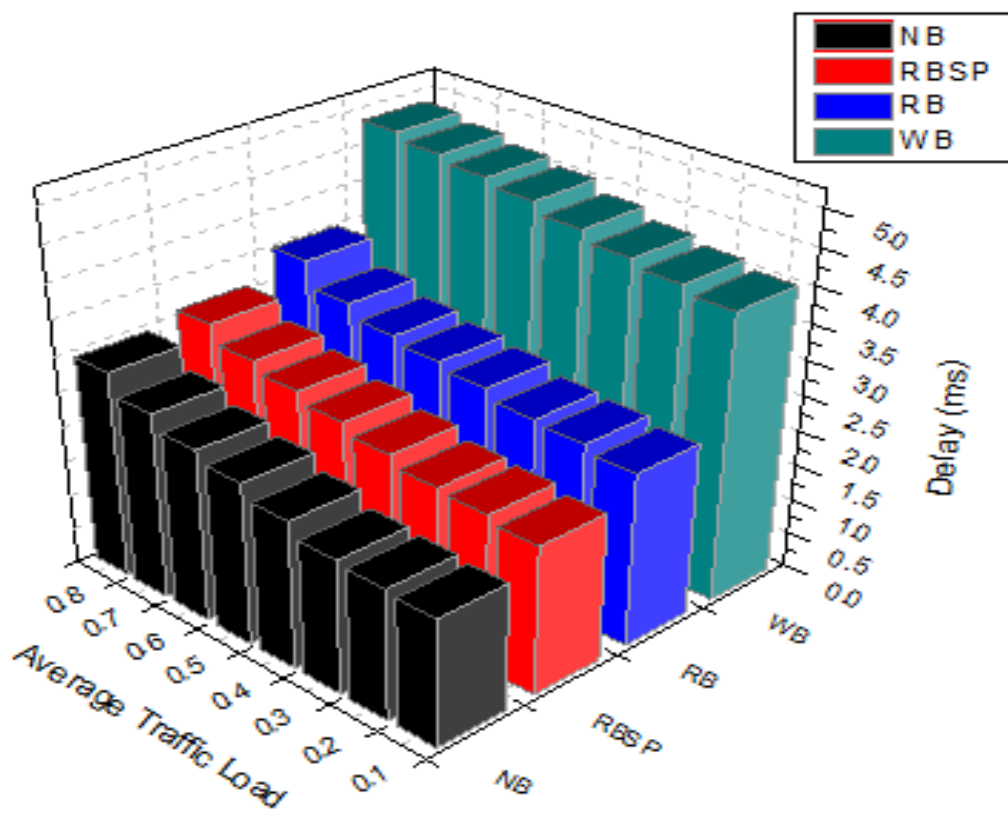
In this architecture, we present four schemes to address the energy saving mechanism in hybrid PON. The first scheme, No Buffer (NB) is based on traditional PON, in which OLT processes the data immediately i.e. without holding. This scheme ensures the fastest delivery of the packet with simple circuitry but consume the most leakage power. In the second scheme, With Buffer (WB), we introduce a buffer of 4 MB capacity with two more transceivers to communicate with OLT and ONU. The buffer will hold instructions and packets so that other functional modules can go into sleep mode. This scheme reduces the power consumption with the compromise of packet delay. In Reduced Buffer (RB) scheme, we add a cache memory of 2 MB capacity with Optical Hardware Limiter (OHL) instead of Buffer. The OHL cuts down the signal strength up to the threshold so that the instructions will not be passed to the OLT until it crosses the threshold level or capacity of the cache. The leakage power and delay is less in this scheme. Finally, we implemented Reduced Buffer with Small Packet size (RBSP) scheme with reducing the size of the packet from 40 KB to 25 KB. This scheme shows a very less power consumption than all other schemes with a marginal delay without affecting the overall network performance.

3.4.2 Result and Discussion

In order to observe the performance of proposed hybrid PON system, the setup is simulated using software OMNET++ with repetition of multiple seeds to present the results with 99% confidence. The model is built up with 10 Gbps data rate for downstream rate and 2.5 Gbps data rate for upstream rate using DSL modem. Other parameters are kept as per specified in [2]. The overall delay of all the schemes with respect to average traffic load for upstream and downstream is shown in figure 3.24.



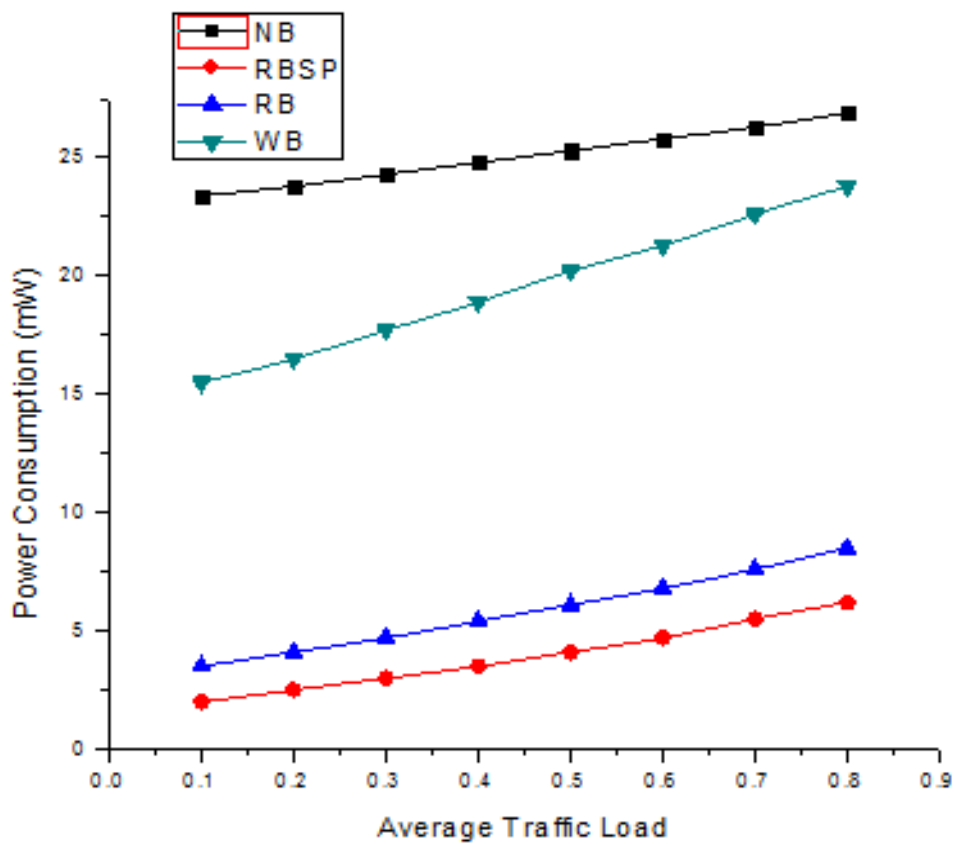
(a)



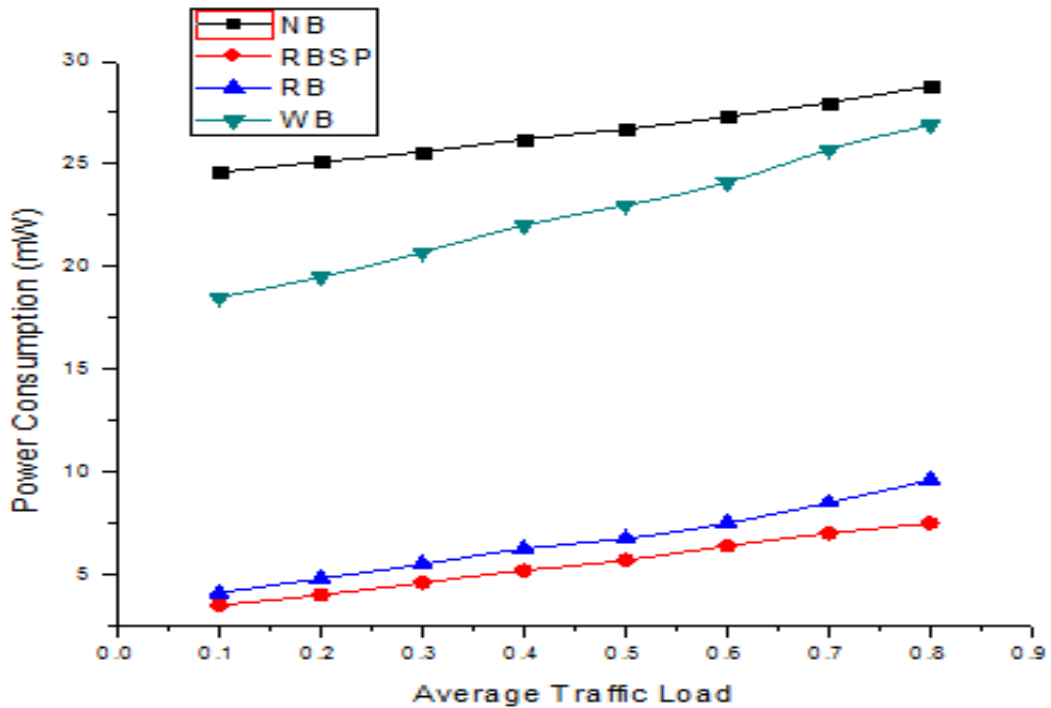
(b)

Figure 3.24: Delay Vs Average Traffic Load for (a) upstream and (b) downstream

It is evident that the delay is sharply increases with increase in traffic load. The “NB” scheme observed the minimum delay form 0.5 to 1.3 ms and 1.85 to 2.95 ms for upstream and downstream with traffic load of 0.1 to 0.8 respectively. A very high delay is observed from 1.9 to 2.7 ms and 4.05 to 4.85 ms in “WB” scheme for upstream and downstream respectively. The “RB” and “RBSP” schemes show a fast delivery of data with a delay of 1.3 to 2.1 ms and 0.7 to 1.55 ms for upstream and 2.45 to 3.5 ms and 2.1 to 3 ms for downstream respectively ensuring the QoS of the proposed network under the tolerance limit of 4 ms [104]. The power consumption by all the schemes with respect to average traffic load for upstream and downstream is shown in figure 3.25.



(a)



(b)

Figure 3.25: Power Consumption Vs Average traffic load for (a) upstream and (b) downstream

It is observed that the “NB” scheme consumes the largest amount of power from 23.4 to 26.9 mW and 24.6 to 28.8 mW for upstream and downstream respectively. The “WB” scheme also consumes large amount of power from 15.5 to 23.8 mW and 18.5 to 26.9 mW for upstream and downstream respectively. The “RB” scheme consumes a very less amount of power from 3.5 to 8.5 mW and 4.1 to 9.6 mW for upstream and downstream respectively. The most energy efficient scheme is “RBSP” with consumption of 2 to 6.2 mW and 3.5 to 7.5 mW with 0.1 to 0.8 traffic load for upstream and downstream respectively.

3.5 Conclusion

Various architectures of hybrid PON have been proposed and evaluated. Triple play services (video, voice and data) have been accessed by 128 ONUs. It has been found that NRZ data format and QAM modulation schemes give better performance. Further, a bidirectional HAPON for different data rates i.e. 1.25, 2.5, 5 and 10 Gbps has been presented. To realize bidirectional transmission in single fiber, a circulator was used to isolate the uplink signals from downlink signals. A network using CCAONUs technique has also been proposed. In most of the PON systems, a laser source is required at ONU.

In the proposed technique, the re-modulation of upstream signal has been done through an extra carrier generated at OLT. The requirement of laser sources at the ONU end has been avoided by using single extra laser source at the OLT in this technique. Four aggressive schemes i.e. NB, WB, RB and RBSP have also been proposed. The performance of these schemes for downstream and upstream data by exploring the relationship between power consumption and average traffic load has been evaluated. RBSP scheme has been found most efficient scheme with consumption of 2 to 6.2 mW and 3.5 to 7.5 mW power at 0.1 to 0.8 traffic load for upstream and downstream respectively.

Chapter 4

Hybrid (WDM/ TDM) PON using Different Amplifiers

In this chapter, the second research objective, i.e. to compare the different amplifiers and find out the most suitable amplifier for hybrid Passive Optical Network (PON) has been investigated. To achieve this objective, we have investigated bidirectional hybrid (WDM/ TDM) PONs for Raman, Semiconductor Optical Amplifier (SOA) and Erbium Doped Fiber Amplifier (EDFA) using polarization modulation technique in swing with QAM at 5 Gbps data rate. BER, Q factor and received optical power are observed for EDFA, SOA and Raman amplifiers in this model at 70 and 80 Km distances. Further, the system is enhanced to 10 Gbps data rate with 128 ONUs using polarization modulation with 16-QAM to utilize the maximum bandwidth. A circulator is used to achieve the bidirectional transmission in the same channel. This chapter is divided into two sections. In first section, hybrid PON system at 5 Gbps data rate is proposed and in second section, the performance of various amplifiers for hybrid PON with 16 QAM at 10 Gbps data rate is discussed.

4.1 Polarization Dependent Bidirectional Hybrid PON utilizing QAM Modulation with Different Amplifiers

Passive Optical Networks (PONs) are of high industrial and technical interest to deal with the ever increasing demand for high data traffic due to non requirement of electrical power at the Remote Nodes (RNs) [66]. Recently, a number of studies have been carried out for improving the overall performance and cost efficiency of optical access networks as shown in table 2.1. To meet the demand of next generation networks, several architectures have been proposed for TDM PON, WDM PON and hybrid (WDM/ TDM) PON [97-99]. In [66], WDM PON was validated over a 60-Km transmission fiber at data rate of 622 Mbit/s only. Further, in another purposed scheme, GEAPON was designed for 56 subscribers at a length of 20 Km with 2 Gbps bit data rate in [56]. A hybrid PON consisting of a 2.5 Gb/s data rate with RSOA for 32 channels up to 50 Km length was proposed in [52]. Due to use of same wavelengths for uplink and downlink, extra tunable devices are required. Moreover, the use of WSSs, FBGs and AWGs increases the complexity and cost of the network. By excluding these components, losses and power requirement can also be reduced. Further, by using two different wavelengths i.e. 1310

and 1550 nm for downlink and uplink respectively, the effect of the non-linearity can be minimized. In the proposed system, we have achieved better results in terms of data rates, output power, quality factor and transmission distance. We have simulated bidirectional hybrid (WDM/ TDM) PONs with 128 ONUs. Using polarization modulation technique in swing with QAM, the system is analyzed for RAMAN, SOA and EDFA at 5 Gbps data rate. It has been observed that EDFA amplifier shows enhanced performance than SOA and RAMAN amplifier by trimming down the consequence of crosstalk respectively for 80 Km with above said ONUs.

4.1.1 System Setup

The block diagram of system setup of hybrid PON is shown in figure 4.1. In the proposed architecture, 128 ONUs can communicate with the central office. The OLT consist of WDM transmitter with different amplifiers.

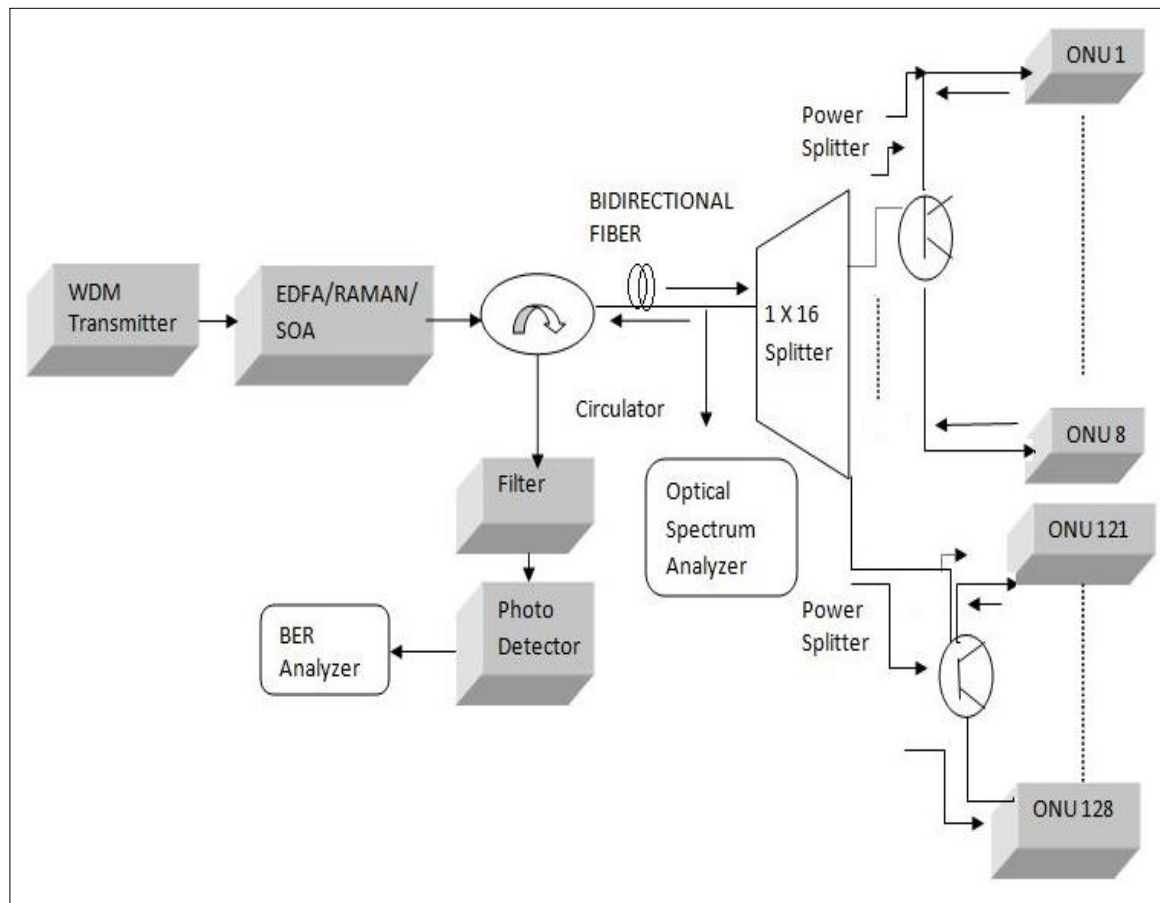


Figure 4.1: Block diagram of system setup for hybrid PON with 128 ONUs

To employ uplink and downlink in the same channel, a circulator (with 3 dB insertion losses, 15 dB isolation) is introduced. To detect the uplink data Bessel's filter and PIN photo detector are used at circulator's end. To reduce the impact of crosstalk (due to

downlink and uplink signals in same channel), two separate wavelengths i.e. 1550 nm and 1300 nm are used for downstream and upstream signals respectively. The data is transmitted through fiber (having 0.2 dB/Km attenuation and 16.75 ps/nm/Km dispersion) with varying length in the channel.

The block diagram of WDM transmitter is shown in figure 4.2. It consists of the Pseudo Random Bit Sequence (PRBS) data generator (to generate 5 Gbps), QAM pre-coder with 5 GHz electrical signal, CW laser source (with generation of laser beam at a frequency of 193.1 THz at 100 GHz channel spacing) and Mach-Zehnder (MZ) modulator. Non return to zero (NRZ) format is used for line coding. The optical signal from CW laser source is splitted into two polarization beams viz. horizontal polarization and vertical polarization via Polarization Beam Splitter (PBS). These signals are further modulated using 16 QAM modulations with Finite Fourier Transform (FFT) with size of 512 and cyclic prefix size of 8. The signals are combined through Polarization Beam Combiner (PBC) and transmitted to the channel.

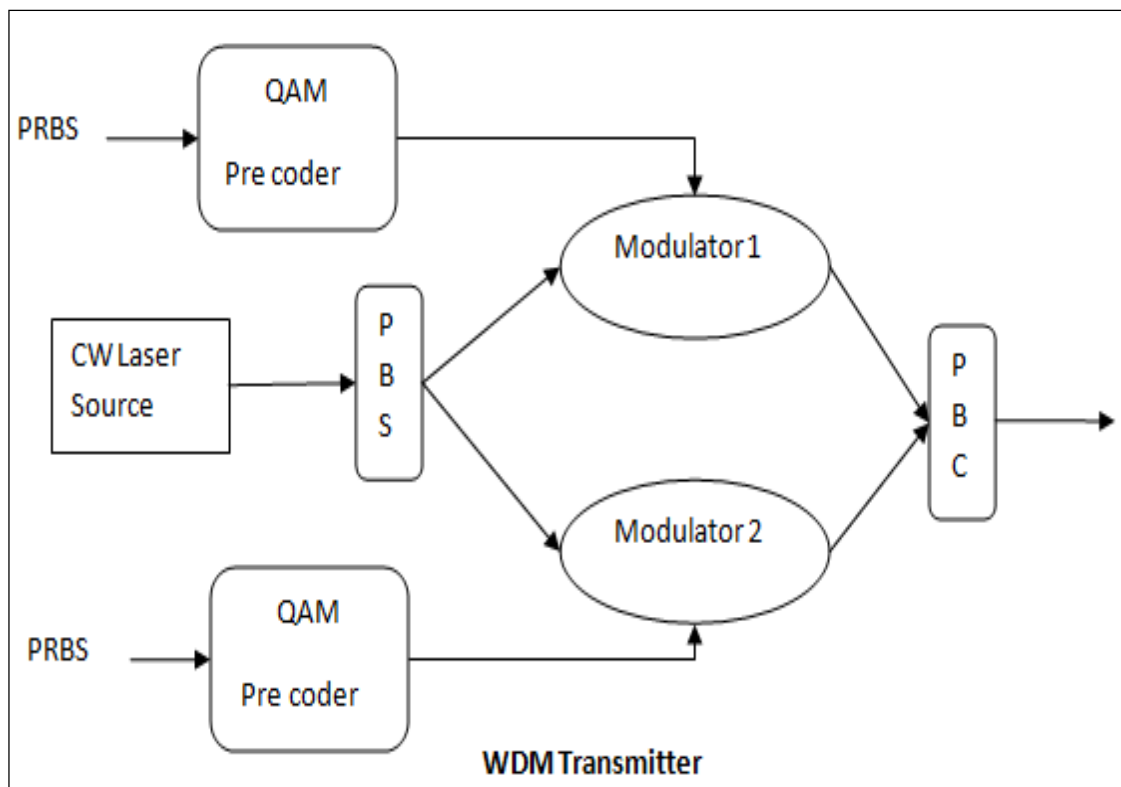


Figure 4.2: The internal structure of WDM transmitter

Passive optical splitters with fiber link are used to transmit the data to 128 ONUs at different time slots. 10 ps time delay is specified to each ONU to receive the signals. The block diagram of ONU is shown in figure 4.3. The downlink signal is decoded with

splitting it into two parts viz. 90° and -90° phase shift using QAM decoder. PIN photo detector with Bessel filter is installed to detect the data.

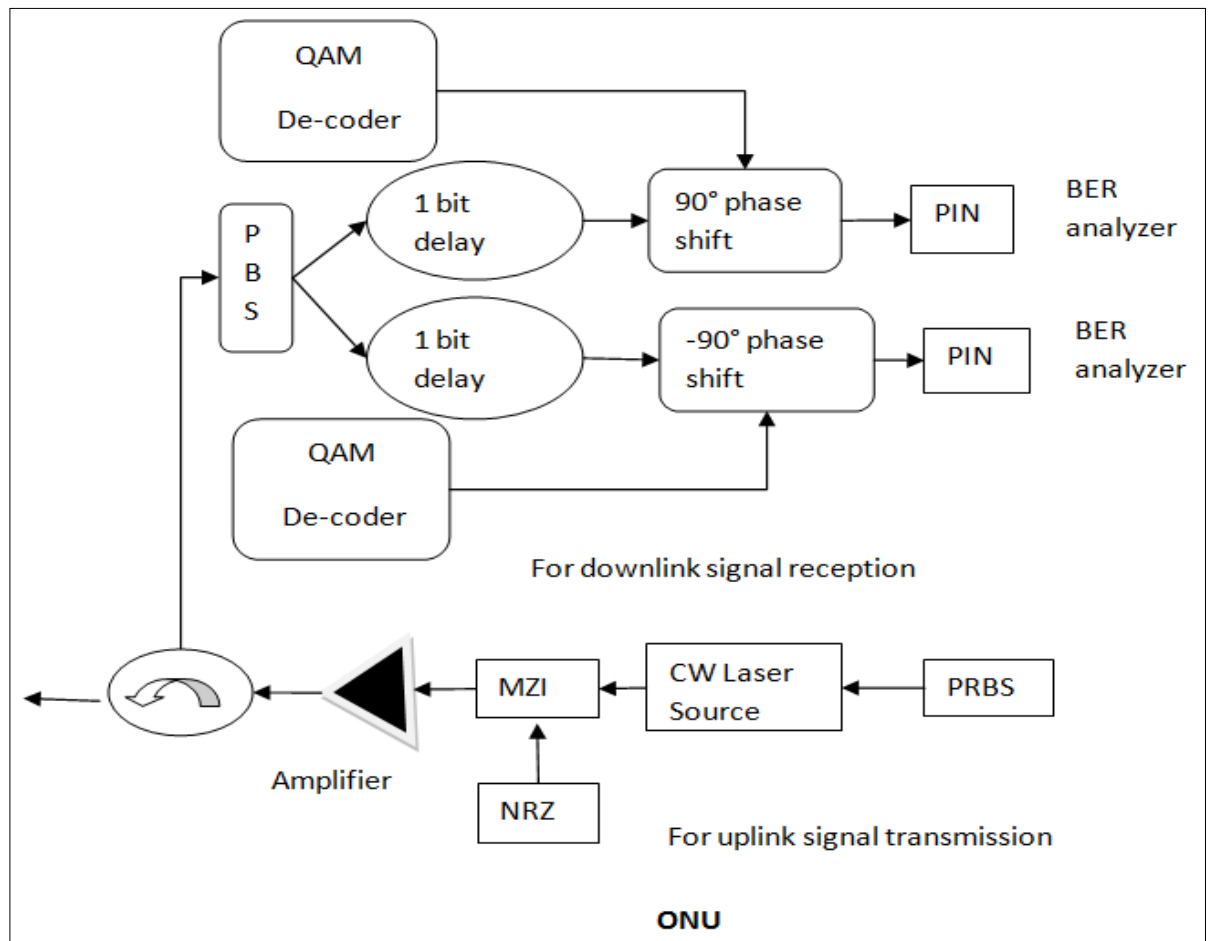


Figure 4.3: The block diagram of ONU

CW laser source and PRBS data source are used to spawn the upstream data. Various analyzers are used for observing the received power, Q factor and BER. The proposed model is investigated for different amplifiers like EDFA, SOA and RAMAN at 5 Gbps data rate.

4.1.2 Result and Discussion

In order to observe the performance of proposed hybrid PON system, the setup is simulated for different optical amplifiers with respect to number of ONUs at 5 Gbps data rate at different distances. The BER, Q factor and received optical power by varying number of ONUs at different optical fiber link length are calculated and represented graphically. Q factor versus number of ONUs for EDFA, SOA and RAMAN amplifiers at 70 Km with 5 Gbps data rate is shown in figure 4.4. It is observed that the Q factor of 14,

6.2 and 0.4 dB with 128 ONUs is achieved by EDFA, SOA and RAMAN amplifiers respectively. It is also shown that Q factor is decreasing with the increase of number of ONUs. The data can be communicated with 120, 90 and 40 ONUs by EDFA, SOA and RAMAN amplifiers respectively with minimum acceptable Q factor [11].

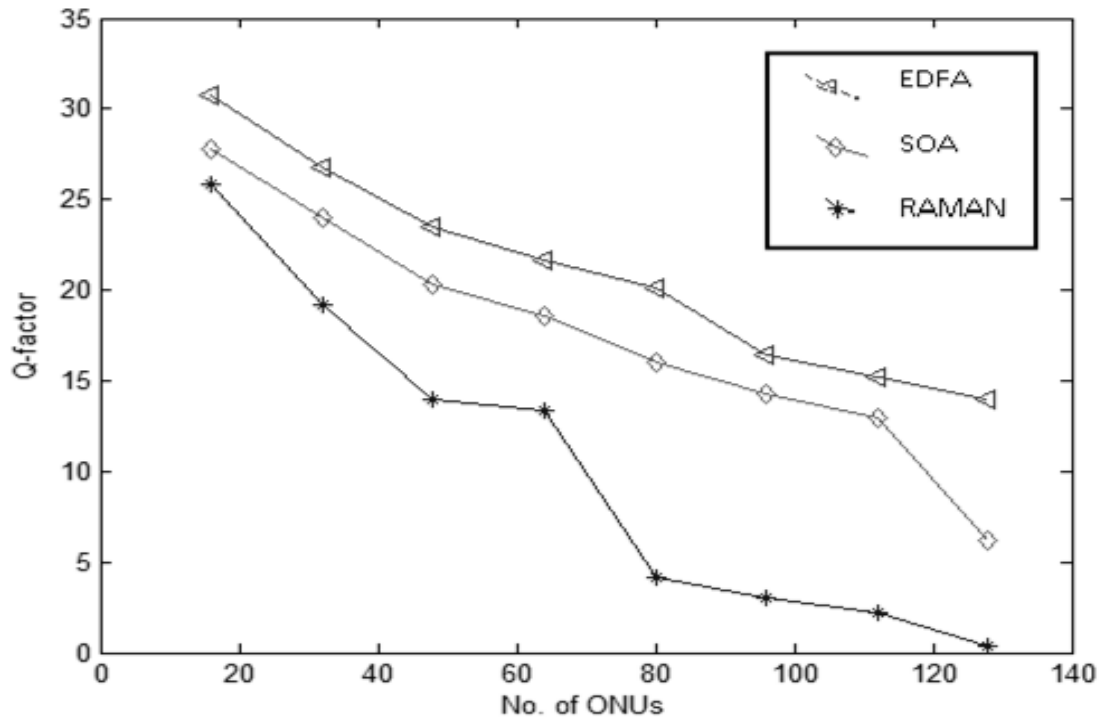


Figure 4.4: Q factor versus number of ONUs at 70 Km with 5 Gbps data rate

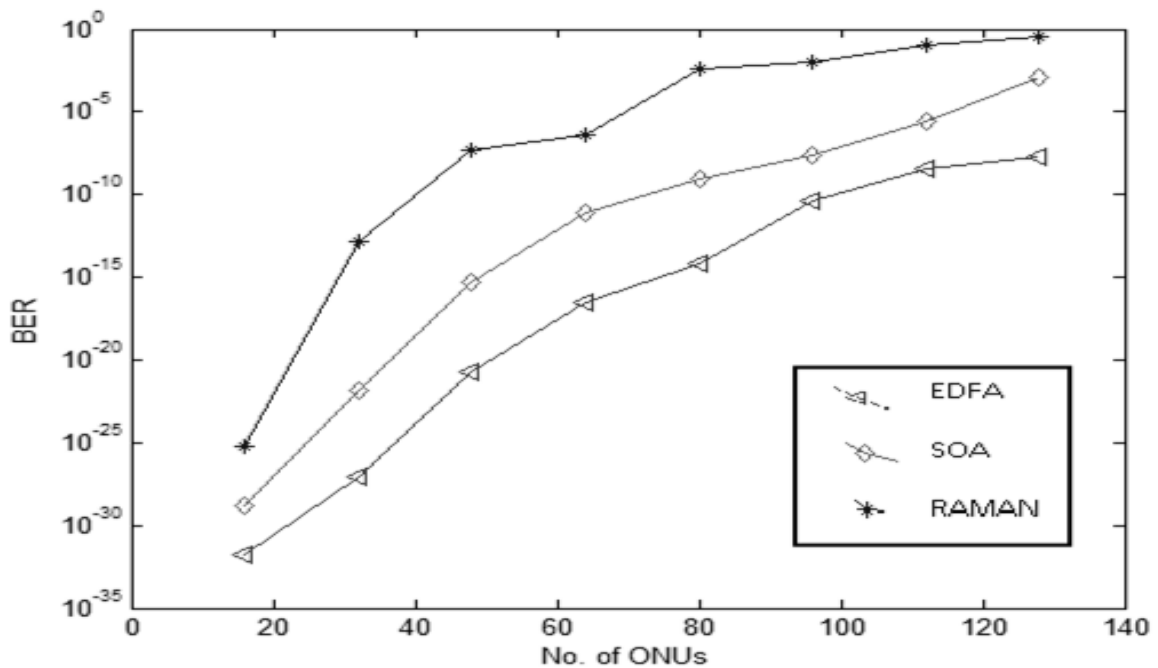


Figure 4.5: BER versus number of ONUs at 70 Km with 5 Gbps data rate

BER versus number of ONUs for EDFA, SOA and RAMAN amplifiers at 70 Km with 5 Gbps data rate is shown in figure 4.5. It is evident that the BER increases with respect to the number of ONUs. The number of ONUs ranges from 20 to 128 in this graph. The impact of different amplifiers on proposed system is analyzed. BER provided by EDFA is 3.8×10^{-9} with 112 ONUs, by SOA is 2.3×10^{-8} with 96 ONUs, by RAMAN is 5.4×10^{-8} with 48 ONUs. If we further increase the number of ONUs, then BER crosses the maximum acceptable limit and hence system is not sufficient to transmit the data. Output power versus number of ONUs for EDFA, SOA and RAMAN amplifiers at 70 Km with 5 Gbps data rate is shown in figure 4.6.

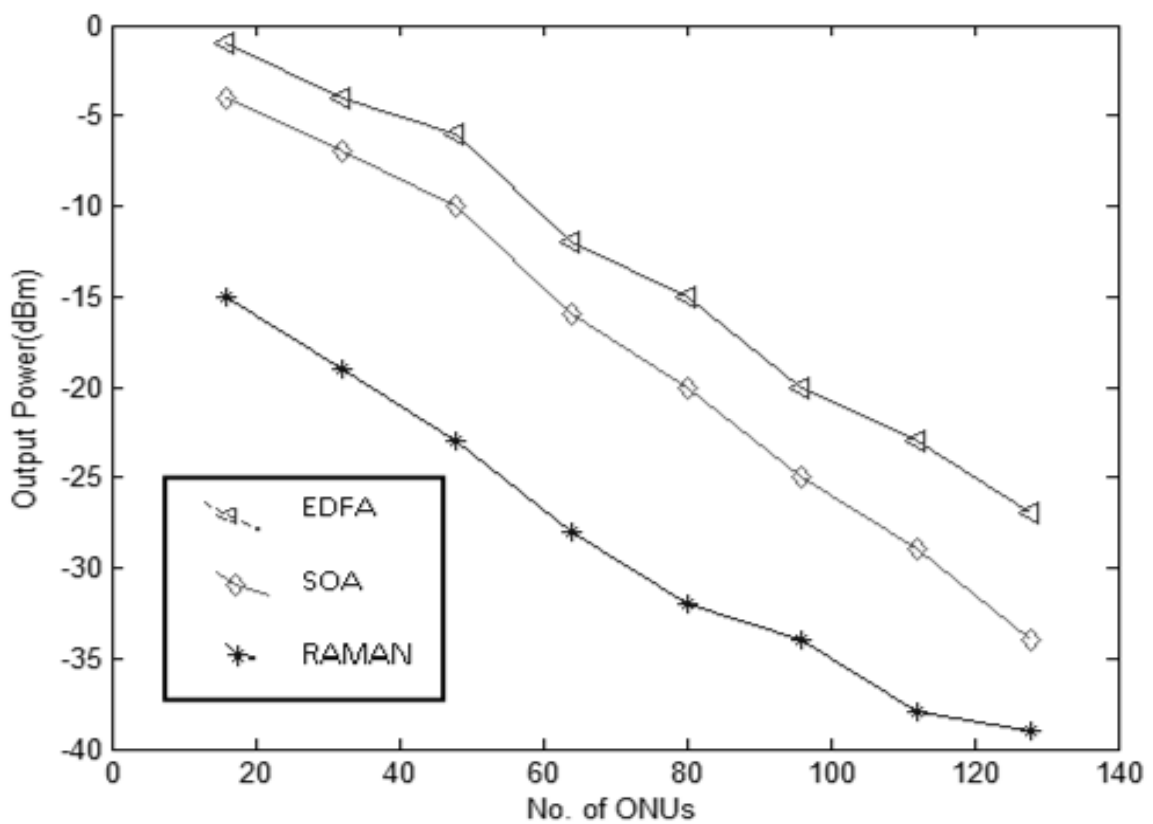


Figure 4.6: Output power versus number of ONUs at 70 Km with 5 Gbps data rate

It is observed that the received optical power of -39, -34 and -27 dBm with 128 ONUs is achieved by EDFA, SOA and RAMAN amplifiers respectively. It is also shown that received power is decreasing with the increase in number of ONUs. Q factor versus number of ONUs for EDFA, SOA and RAMAN amplifiers at 80 Km with 5 Gbps data rate is shown in figure 4.7.

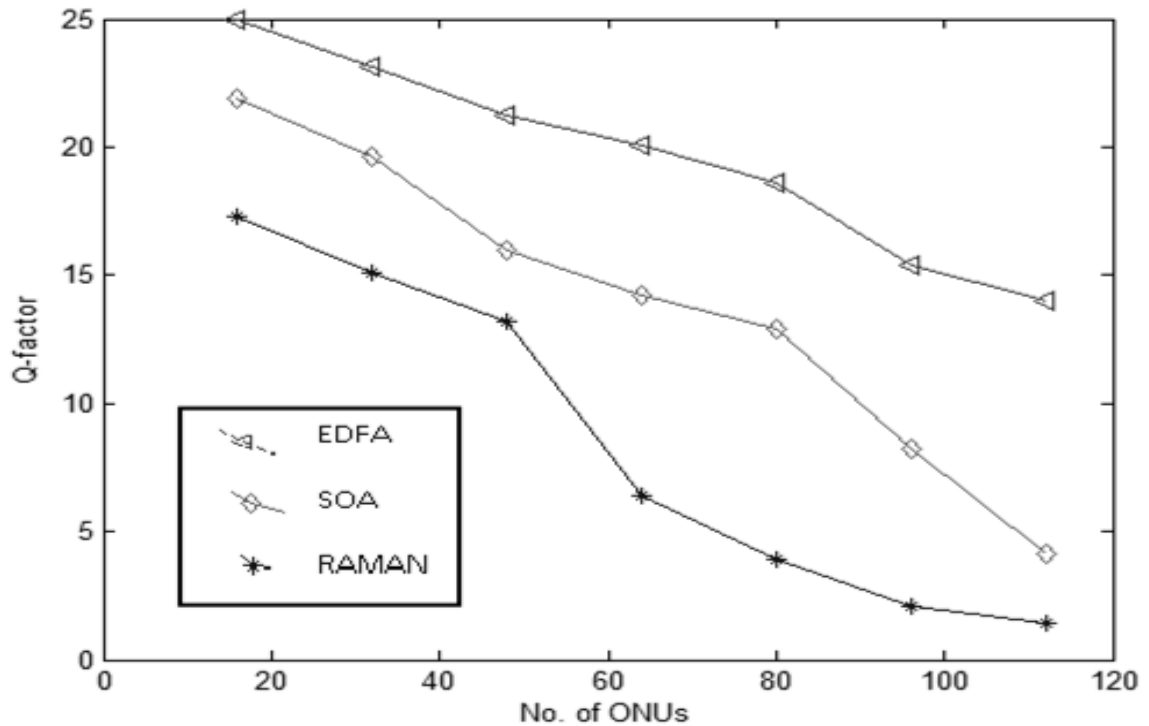


Figure 4.7: Q factor versus number of ONUs at 80 Km with 5 Gbps data rate

It is observed that the Q factor of 14.2, 4.1 and 1.4 dB with 112 ONUs is achieved by EDFA, SOA and RAMAN amplifiers respectively. It is also shown that Q factor is decreasing with the increase in number of ONUs. The data can be communicated with 110, 60 and 35 ONUs by EDFA, SOA and RAMAN amplifiers respectively with minimum acceptable Q factor. BER versus number of ONUs for EDFA, SOA and RAMAN amplifiers at 80 Km with 5 Gbps data rate is shown in figure 4.8.

It is evident that BER increases with respect to the number of ONUs. The number of ONU ranges from 20 to 112 in this graph. BER provided by EDFA is 2.3×10^{-9} with 96 ONUs, by SOA is 4.1×10^{-9} with 64 ONUs, by RAMAN is 1.9×10^{-9} with 40 ONUs. If we further increase the number of ONUs, then the BER crosses the maximum acceptable limit and hence system is not sufficient to transmit the data.

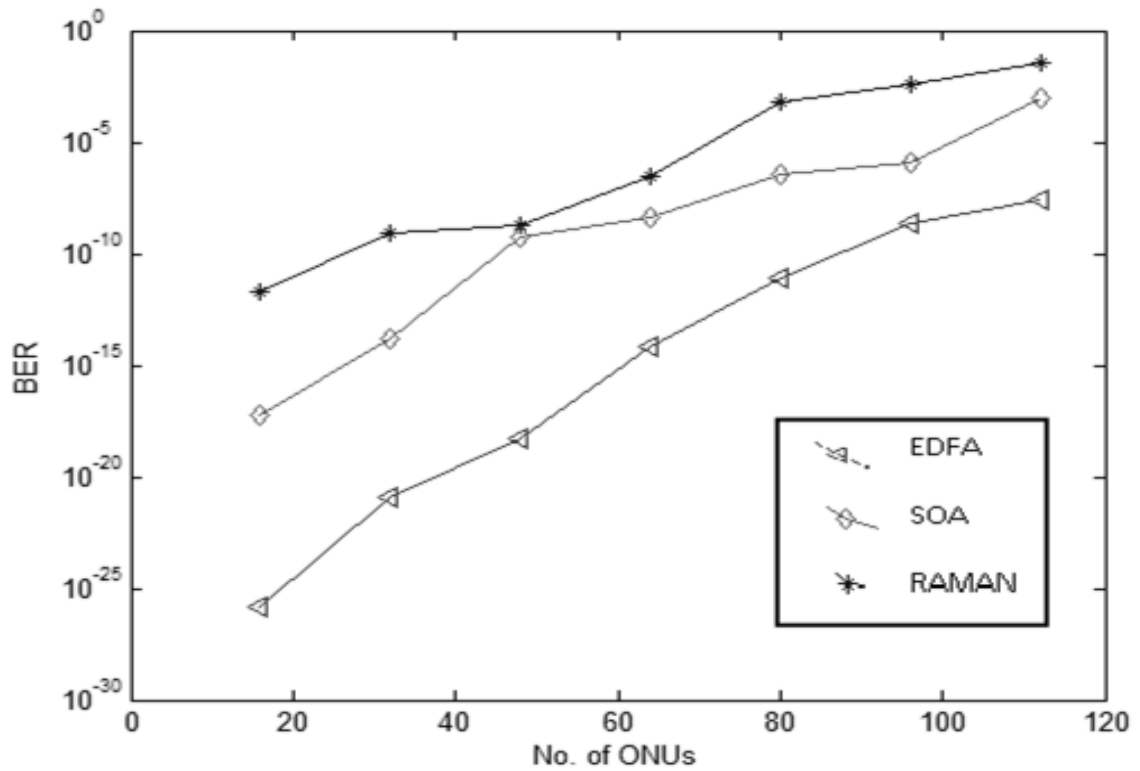


Figure 4.8: BER versus number of ONUs at 80 Km with 5 Gbps data rate

Output power versus number of ONUs for EDFA, SOA and RAMAN amplifiers at 80 Km with 5 Gbps data rate is shown in figure 4.9.

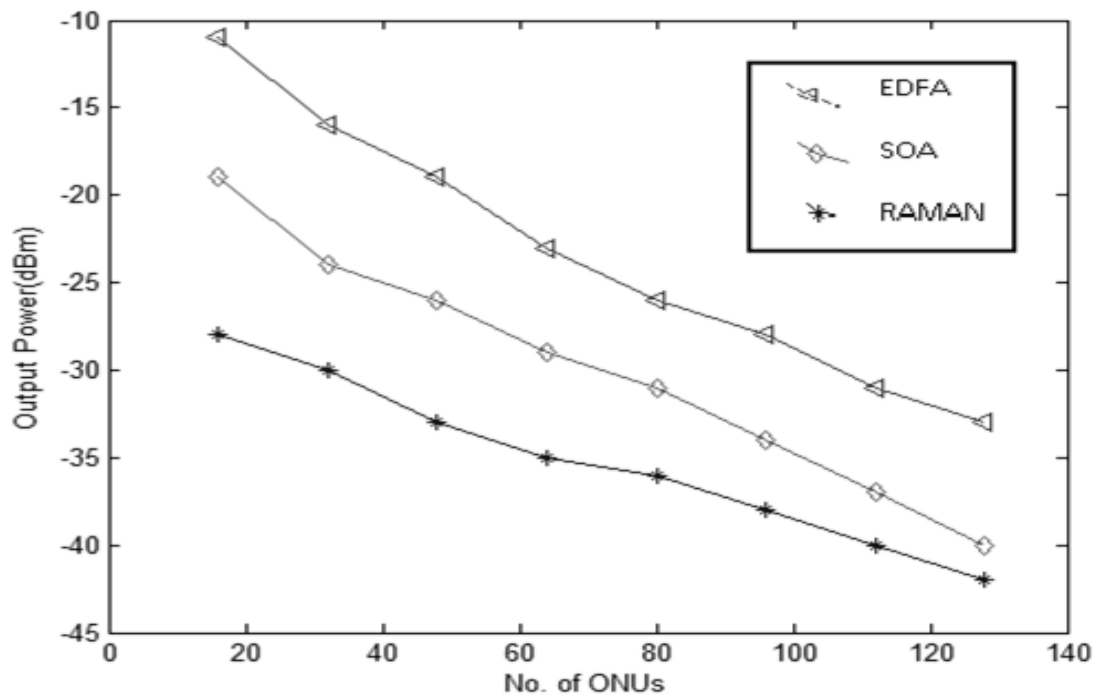


Figure 4.9: Output power versus number of ONUs at 80 Km with 5 Gbps data rate

It is observed that the received optical power of -42, -40 and -33 dBm with 128 ONUs is achieved by EDFA, SOA and RAMAN amplifiers respectively. It is also shown that received power is decreasing with the increase in number of ONUs.

4.2 Bidirectional HPON with 16-QAM Modulation Technique

Now-a-days, the end-consumer is demanding large bandwidth to access networks to transmit huge contents at high speed. Due to less power requirements, PONs are becoming the first choice for such networks [90]. In literature, we have studied the research work on PONs. Considering [105], a protection scheme for transmitters in WDM-PON was proposed using a FP-LD with 2.5 Gbit/s data rate for downstream transmission over 10 Km distance. In [99] TDM-PON was proposed with four directly modulated 2.5 Gb/s FP-LDs to transmit data up to 25 Km. In this section, we presented hybrid PON architecture with 10 Gb data rate at longer distances. Two different wavelengths 1550 nm and 1300 nm are used for downlink and uplink data to avoid the use of extra tunable devices and reduce the effect of non linearity. Also, the non employment of various complex components like WSSs, FBGs and AWGs (increase the complexity and cost of the network), is achieved for the sake of simplicity and flexibility. Further, the system is investigated with different types of optical amplifiers to find out the best suitable for the same.

4.2.1 System Setup

The block diagram of hybrid PON with 128 ONUs is shown in figure 4.10. At the transmission section, PRBS data source is used as data source to generate 10 Gbps data rate. Different amplifiers like EDFA, SOA and RAMAN are used compared for the proposed system at 10 Gbps data rate.

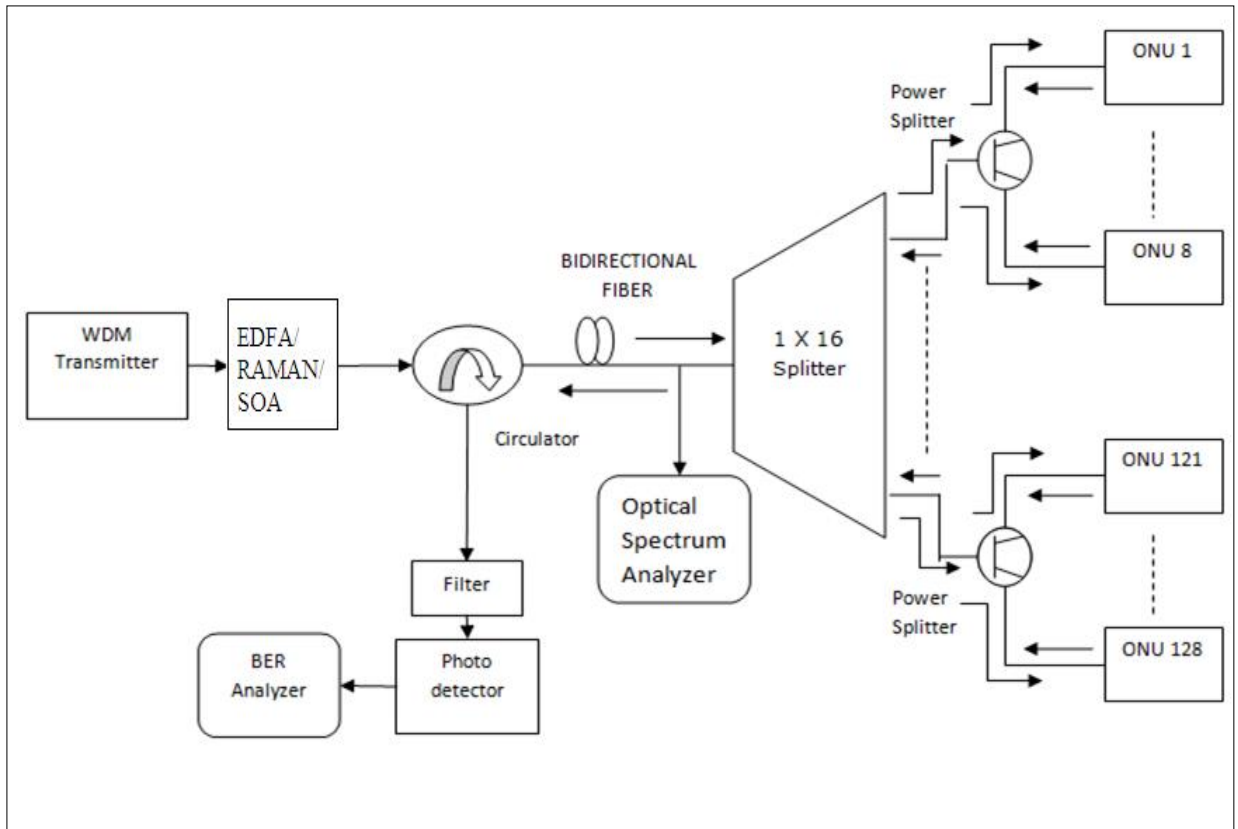


Figure 4.10: Block diagram of system setup for hybrid PON with 128 ONUs

A circulator (with 3 dB insertion losses, 15 dB isolation) is employed for making possible bidirectional (upstream and downstream) data in same channel. For detection of the upstream data, Bessel's filter and PIN photo detector are used.

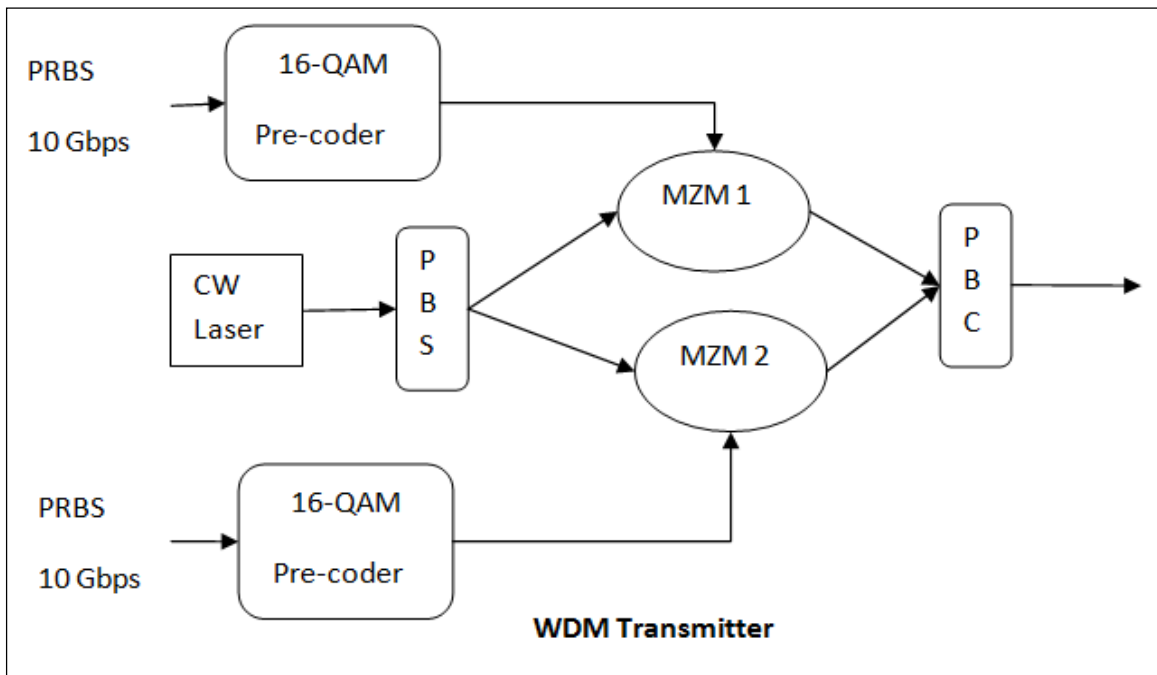


Figure 4.11: The internal structure of WDM transmitter

A wavelength of 1550 nm is used to transmit downstream data and 1300 nm for upstream data so that the impact of crosstalk can be minimized. The optical fiber with 0.2 dB/km attenuation and 16.75 ps/nm/km dispersion is installed and simulation is done at different lengths of the fiber. The block diagram of WDM transmitter is shown in figure 4.11. The signal is generated using an electrical driver and CW laser source (with 193.1 THz frequency at 100 GHz channel spacing). The 16-QAM pre-coder with 5 GHz electrical signal is used to modulate the signal with Mach-Zehnder (MZ) modulator (an excess loss of -3 dB). NRZ format is used for line coding. The optical signal from CW laser source is sputtered into two polarization beams viz. horizontal polarization and vertical polarization via Polarization Beam Splitter (PBS). These signals are further modulated using 16 QAM modulations with FFT with size of 512 and cyclic prefix size of 8.

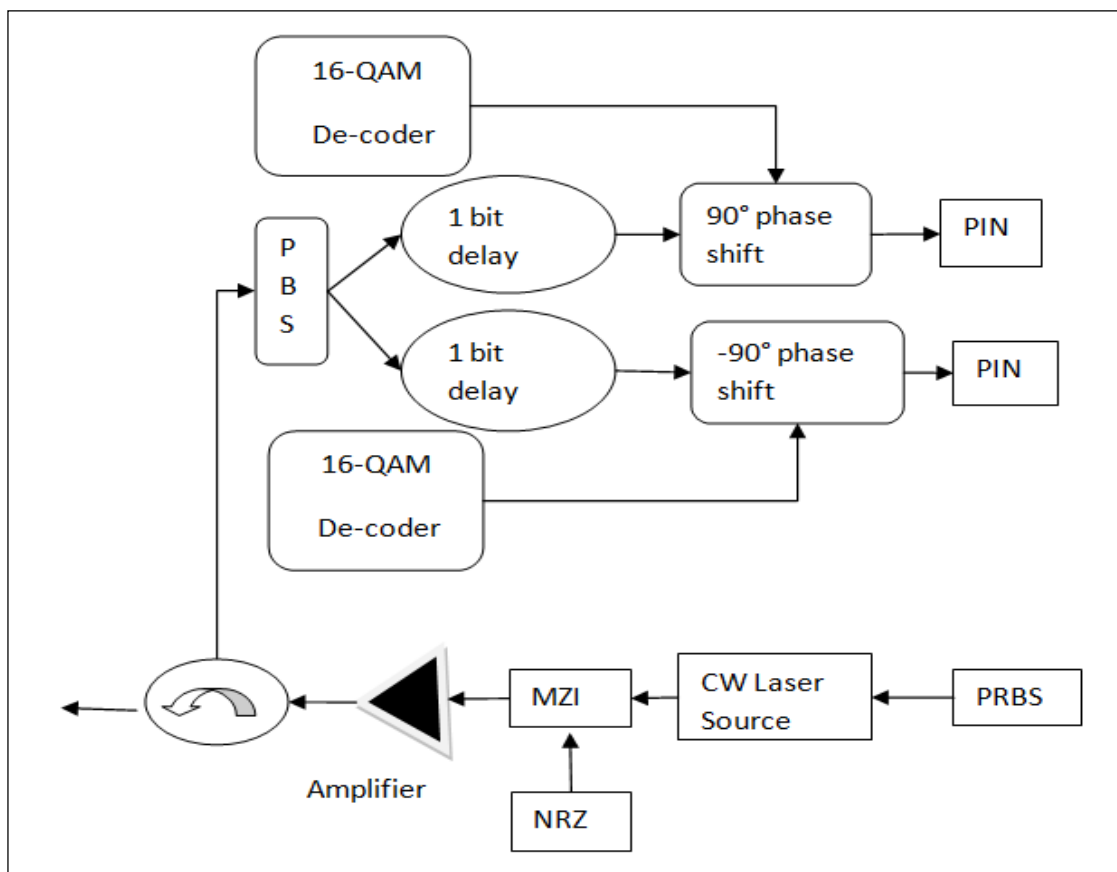


Figure 4.12: The block diagram of ONU

The block diagram of ONU is shown in figure 4.12. QAM decoder is used to decode downstream signals at 90° and -90° phase shift. PIN photo detector with Bessel filter is installed to detect the data. 10 ps time delay is given to each ONU to receive the signal in each power splitter module. To keep the ONU simple and cost effective, CW laser source

with PRBS data source are used to generate the upstream data. Various analyzers are used for observing the received power, Q factor and BER.

4.2.2 Result and Discussion

The hybrid PON system has been investigated for different optical amplifiers (RAMAN, EDFA and SOA) with respect to number of ONUs at 10 Gbps data rate at 40 and 50 Km distances. The setup is simulated and various performance parameters like BER, Q factor and received optical power with different number of ONUs are observed and shown.

Q factor versus number of ONUs for EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 40 Km is shown in figure 4.13.

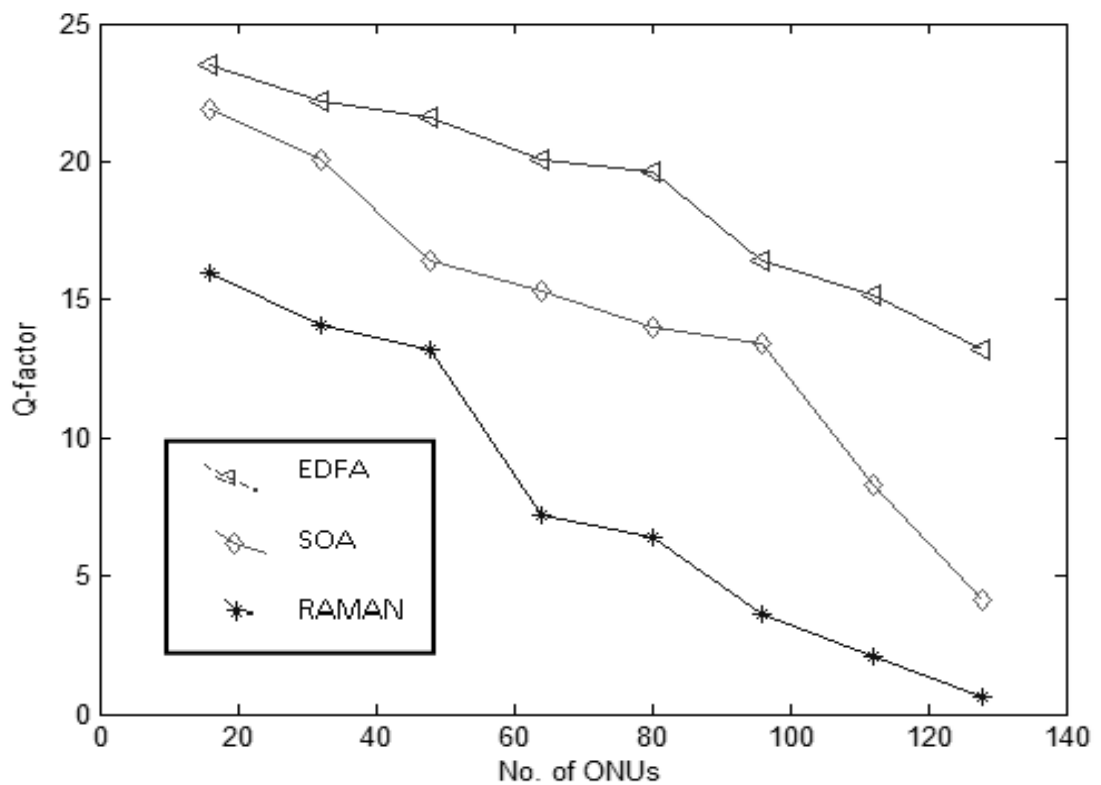


Figure 4.13: Q factor versus number of ONUs with 10 Gbps data rate at 40 Km

It is observed that the Q factor of 13.2, 4.1 and 0.6 dB with 128 ONUs is achieved by EDFA, SOA and RAMAN amplifiers at 40 Km with 10 Gbps respectively. It is also observed that Q factor is decreasing with the increase of ONUs. The data can be communicated with 120, 96 and 48 ONUs by EDFA, SOA and RAMAN amplifiers respectively with minimum acceptable Q factor. BER versus number of ONUs for EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 40 Km is shown in figure 4.14.

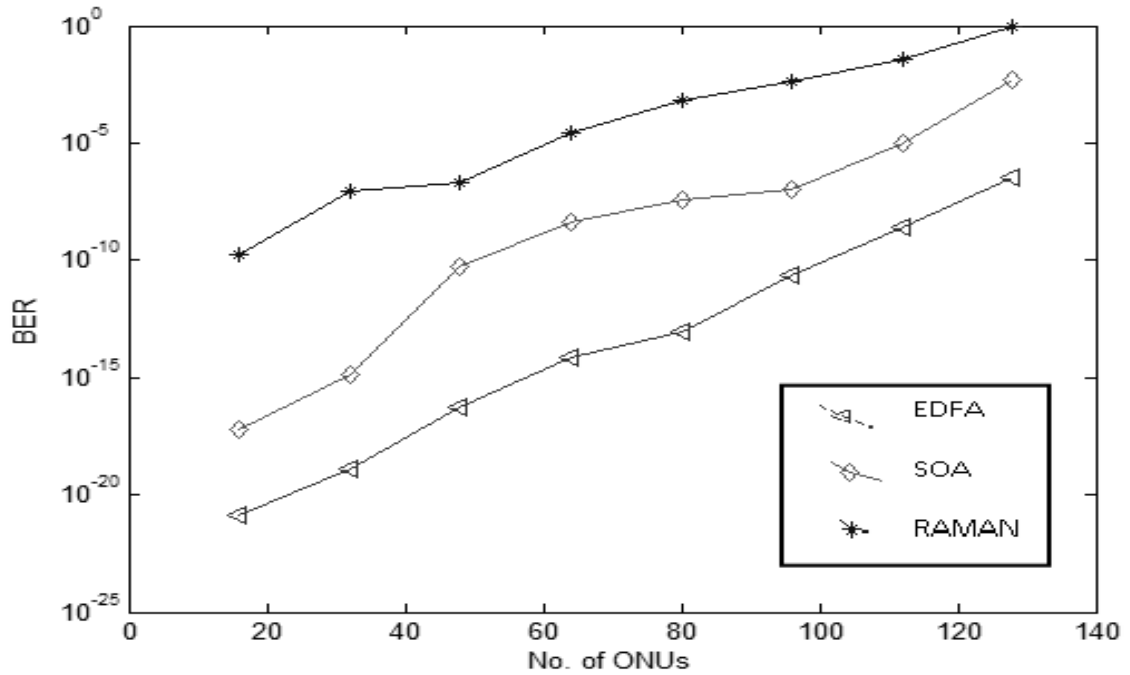


Figure 4.14: BER versus number of ONUs with 10 Gbps data rate at 40 Km

As shown in the figure 4.14, it is evident that the BER increases with increase in the number of ONUs. BER of 2.6×10^{-9} by EDFA with 112 ONUs, 3.6×10^{-8} by SOA with 96 ONUs and 9.2×10^{-8} by RAMAN by 48 ONUs are observed with 10 Gbps data rate at 40 Km. Output power versus number of ONUs for EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 40 Km is shown in figure 4.15.

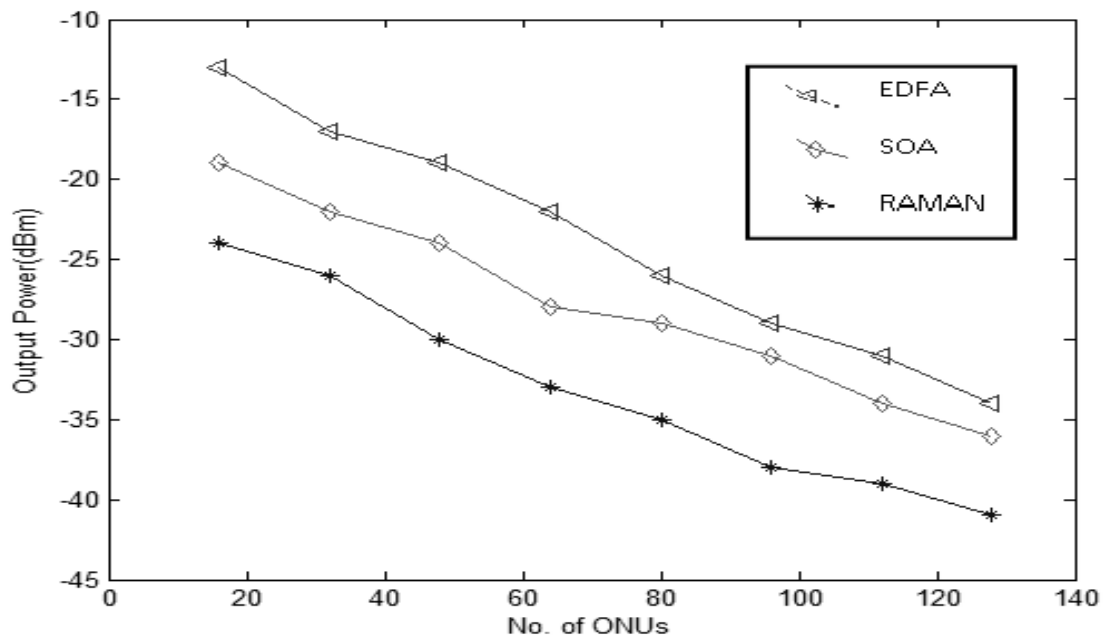


Figure 4.15: Output power versus number of ONUs with 10 Gbps data rate at 40 Km

As shown in figure 4.15, it is evident that the received optical power of -41, -36 and -34 dBm with 128 ONUs is obtained by EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 40 Km respectively. It is also shown that received power is decreasing with the increase in number of ONUs. Q factor versus number of ONUs for EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 50 Km is shown in figure 4.16.

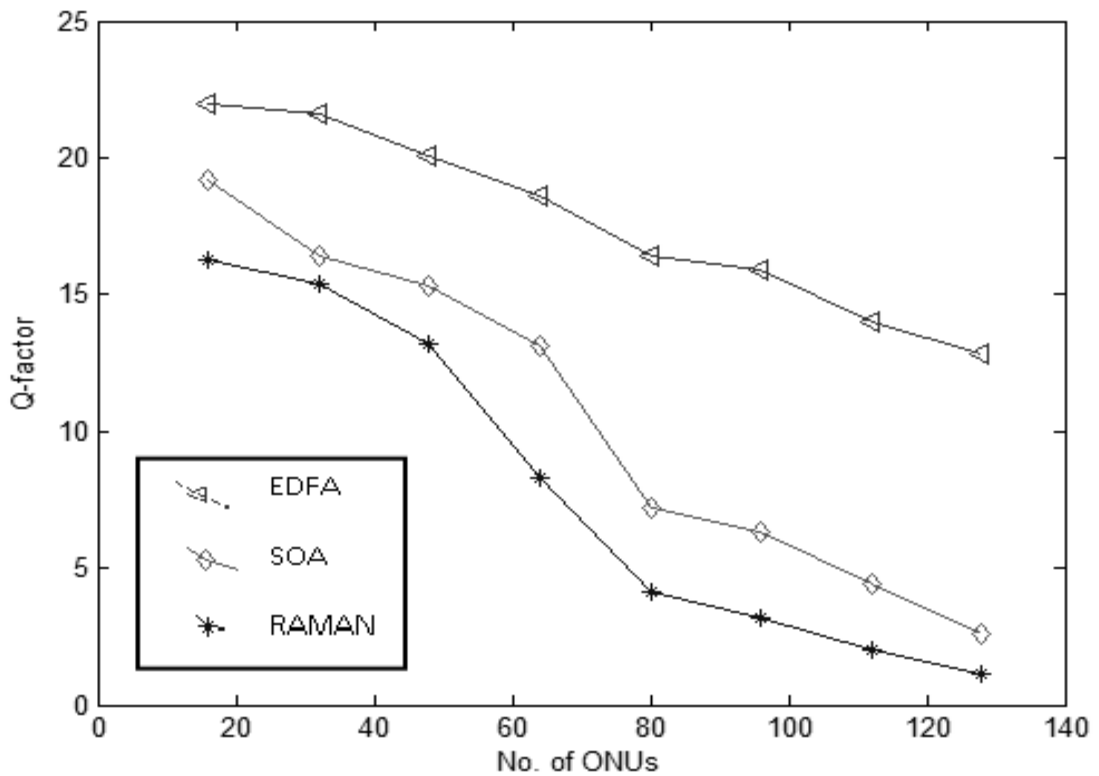


Figure 4.16: Q factor versus number of ONUs with 10 Gbps data rate at 50 Km

It is observed that the Q factor of 12.8, 2.6 and 1.1 dB with 128 ONUs is achieved by EDFA, SOA and RAMAN amplifiers at 50 Km with 10 Gbps respectively. It is also observed that Q factor is decreasing with the increase in number of ONUs.

BER versus number of ONUs for EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 50 Km is shown in figure 4.17. It is evident that the BER increases with increase in the number of ONUs. The BER of 2.6×10^{-8} by EDFA with 112 ONUs, 4.1×10^{-8} by SOA with 64 ONUs and 9.2×10^{-9} by RAMAN by 32 ONUs are observed with 10 Gbps data rate at 50 Km.

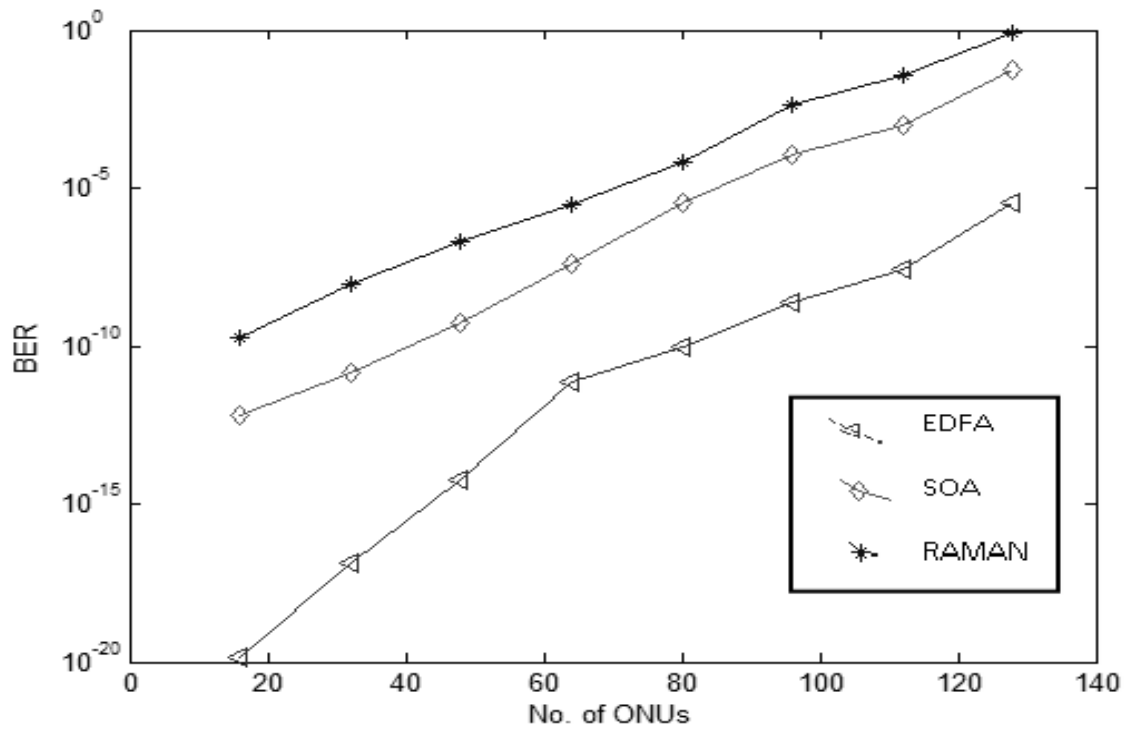


Figure 4.17: BER versus number of ONUs with 10 Gbps data rate at 50 Km

Output power versus number of ONUs for EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 50 Km is shown in figure 4.18.

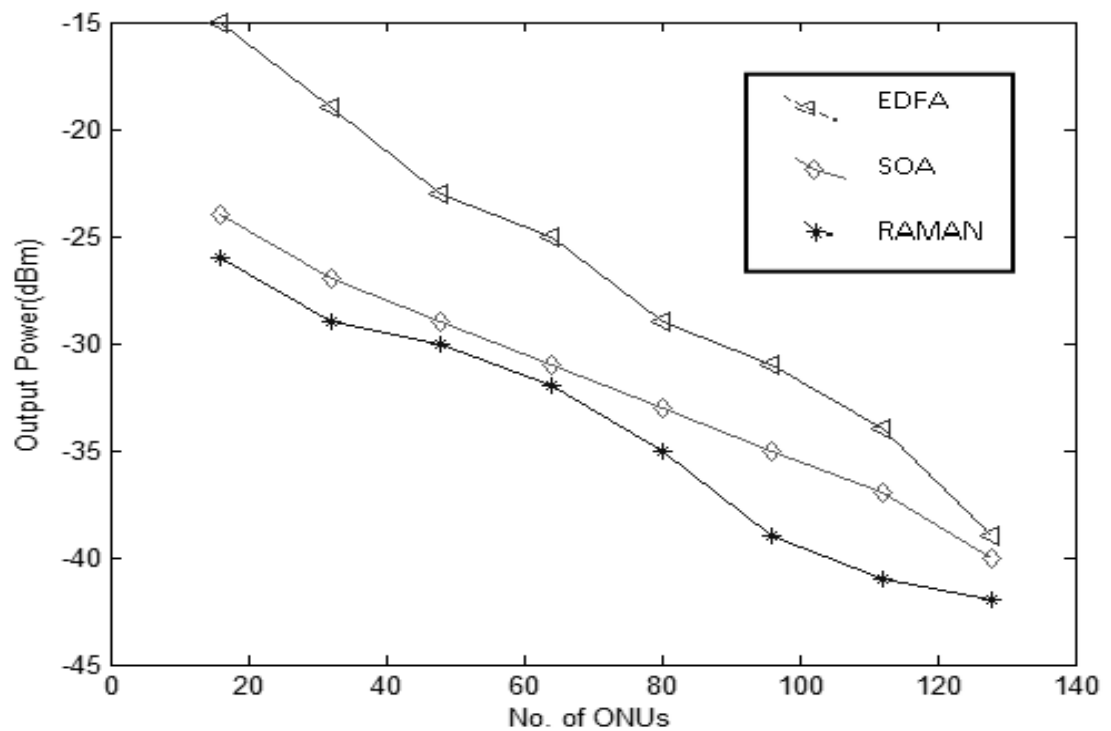


Figure 4.18: Output power versus number of ONUs with 10 Gbps data rate at 50 Km

As shown in figure 4.18, it is evident that the received optical power of -42, -40 and -39 dBm with 128 ONUs is obtained by EDFA, SOA and RAMAN amplifiers with 10 Gbps data rate at 50 Km respectively. It is also shown that received power is decreasing with the increase in number of ONUs.

4.3 Conclusion

A bidirectional hybrid PON for Raman, SOA & EDFA amplifiers using polarization modulation technique with QAM at 5 Gbps data rate has been investigated. It has been shown that the signal with 5 Gbps data rate can be transmitted and received by 120, 90 & 40 ONUs up to 70 Km and 110, 60 & 35 ONUs up to 80 Km transmission distance with EDFA, SOA and Raman amplifiers respectively with maximum acceptable BER. Further, the system has also been enhanced to 10 Gbps data rate with 128 ONUs. Polarization modulation with 16-QAM has been used to utilize the maximum bandwidth. It has been found that the data can be transmitted and received with 120, 96 and 48 ONUs up to 40 Km and 112, 64 and 40 ONUs up to 50 Km transmission distance by EDFA, SOA and RAMAN amplifiers respectively with minimum acceptable Q factor.

Chapter 5

Investigation and Mitigation of Nonlinearities induced in HPON

This Chapter deals with the techniques to mitigate the effect of nonlinearities in hybrid Passive Optical Network (PON) which is the third research objective of the thesis. We have investigated bidirectional hybrid PON using CCAONUs technique. The system is analyzed theoretically in the presence of crosstalk due to various fiber nonlinearities like Cross Phase Modulation (XPM), Four Wave Mixing (FWM), Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS). Further, an analytical model to calculate the effect of XPM, FWM, SRS and SBS is presented. The impact of nonlinearities is also mitigated in the proposed network. The effect of crosstalk is mitigated by designing network for Mixed Line Rates (MLRs) i.e. 10/ 20/ 40 Gbps. Further, the investigation is focused on uniform channel spacing and mixed channel spacing for MLRs. It is found that mixed channel spacing for MLRs shows better results than conventional uniform channel spacing. The chapter is systematized in two segments. An analytical model to investigate nonlinearities in hybrid PON has been given in section 5.1 and a system based on MLRs is proposed in section 5.2.

5.1 HPON using CCAONUs Technique in the Presence of Fiber Nonlinearities

With respect to the new generation access networks, the researchers are focusing on developing the networks to support high data rate, large data bandwidth, enhanced security and scalability for the future applications [98]. PON systems with Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM) techniques are proven as a promising solution to provide a cost-effective, highly flexible, expandable and scalable network for all the end subscribers [52, 91].

Most of the networks are based on the principle of same wavelengths for both downstream and upstream transmissions. Due to this, the system is vulnerable to reflections caused by nonlinearities [70]. When multiple wavelengths propagate in the fiber, various nonlinearities such as XPM, FWM, SRS and SBS lead to crosstalk between

different wavelengths and generate significant amount of nonlinear crosstalk between adjacent channels because they are very closely spaced [87].

Meihua Bi et al. [69] investigated ultra-dense WDM-PON for 12 numbers of ONU at 1.25 Gbps data rate with different channel spacing. The effect of nonlinearity has been analyzed and mitigated for the proposed system by aligning the signals of all the channels with respect to different channel spacing. Abdelfettah Chenika et al. [68] investigated WDM PON using NRZ-DQPSK modulation scheme for upstream and ASK modulation scheme for downstream for the effect of Rayleigh and Brillouin backscattering. Four channels of 10 Gbps have been transmitted over 30 km optical fiber length. N. Kumar et al. [87] has been evaluated a SCM–WDM communication link at different modulation frequencies, transmission lengths and optical powers for variety of fiber for XPM-induced crosstalk. Various results were shown that XPM-induced crosstalk dominates at high frequency.

As per the literature survey, the effect of crosstalk for WDM PON has been investigated. The crosstalk effect for hybrid PON has been rarely done. The combined effect of all the nonlinearities is not done yet. In this section, we focus on the analysis of nonlinear crosstalk caused by XPM, FWM, SRS and SBS. Further, we proposed bidirectional hybrid (WDM/TDM) PON using CCAONUs. Different wavelengths for downstream and upstream i.e. 1550 nm and 1300 nm are used to minimize the crosstalk effect of same wavelength in the fiber respectively. Various results in 2D and 3D are shown for the impact of these nonlinearities with Carrier to Noise Ratio (CNR), input power, received output power, BER and number of ONUs.

5.1.1 System Theoretical Analysis

To fulfill the requirements of new generation access networks, a number of wavelength channels are propagated in the same fiber. Different amplifiers are employed to authenticate the transmission at longer distances. All these system requirements cause nonlinear impairments such as XPM, FWM, SRS and SBS. These nonlinear effects dominate the performance in both digital and analog systems.

5.1.1.1 Theoretical Analysis of XPM

XPM is induced in optical network systems due to phase inflection of the optical field rooted by a neighboring optical signal propagating within the same fiber. The non linear

effect of the network can be analyzed using Non Linear Schrodinger Equation (NLSE).

Considering an optical signal $A(t,z)$ propagating in the fiber [106,107]:

$$\frac{\partial A(t,z)}{\partial z} + \frac{\alpha_1}{2} A_1(t,z) + \frac{i}{2} \beta_{21} \frac{\partial^2 A_1(t,z)}{\partial T^2} - \frac{1}{6} \frac{i\beta_{31} \partial^3 A_1(t,z)}{\partial T^3} = i\gamma [9 |A_1|^2 |A_2|^2 |A_3|^2] A_1(t,z) + \Psi_\omega \quad \text{----(5.1)}$$

Where α_n represents the optical attenuation coefficient of the nth channel, β_{in} represents the nth channel's ith order dispersion parameter and the channel's non linearity coefficient (γ) can be expressed as

$$\gamma = \frac{2\pi n_2}{\lambda_2 A_{\text{eff}}} \quad \text{----(5.2)}$$

Where n_2 represents the non linear refractive index, λ represents the optical signal wavelength, A_{eff} represents the effective core area of the fiber. Through linear approximation to calculate the effect of inter channel crosstalk, the equation (5.1) can be expressed as [87]:

$$\frac{\partial A(t,z)}{\partial z} = -\frac{\alpha_1}{2} A_1(t,z) - \frac{i}{2} \beta_{21} \frac{\partial^2 A_1(t,z)}{\partial T^2} + \frac{1}{6} \frac{i\beta_{31} \partial^3 A_1(t,z)}{\partial T^3} + i\gamma [9 |A_1|^2 |A_2|^2 |A_3|^2] A_1(t,z) + \Psi_\omega \quad \text{----(5.3)}$$

The Fourier Transform of the above equation for translating in frequency domain,

$$\frac{\partial A(\omega,z)}{\partial z} = \left(\frac{\alpha_1}{2} + \frac{i}{2} \right) - \frac{i\omega^3 \beta_{31}}{6} + \frac{i n_2 \omega_0}{c A_{\text{eff}}} [9 P(\omega, 0) e^{-\alpha L}] A_1(\omega, z) \quad \text{----(5.4)}$$

Where $A(\omega,z)$ is the Fourier Transform of $A(t,z)$, $P(\omega,0)$ is the power spectrum of the pump signal. In equation (5.4), the first term $\left(\frac{\alpha_1}{2} + \frac{i}{2} \right)$ accounts for attenuation and linear phase delay. The second and third term are responsible for phase modulation by the pump signal and the phase noise to intensity noise conversion at the end of the fiber $z = L$ due to chromatic dispersion. The mathematical expression to calculate XPM induced crosstalk power can be represented as

$$P(\omega,L) = 4 \gamma P_j(0) e^{-\alpha L} \cdot \int_0^L 9 P(\omega, 0) \cdot e^{-\alpha L} \times \left\{ \frac{\sin(\beta \omega^2 / 2)}{\alpha + j\beta \Delta \lambda \omega} \right\} \quad \text{----(5.5)}$$

Where $\Delta \lambda$ is wavelength spacing and can be represented as

$$\Delta \lambda = \Delta \omega \lambda^2 / c \quad \text{----(5.6)}$$

By taking the magnitude of $P(\omega,L)$ and ignoring α^2 being too small, we have

$$|P(\omega, L)| = 8 \pi \gamma P_j(0) P_k(\omega) e^{-\alpha L} \left\{ \frac{\sin(\beta\omega^2/2)}{\beta\Delta\lambda\omega} \right\} \quad \text{----(5.7)}$$

5.1.1.2 Theoretical Analysis of FWM

It is a non linear process that transfers energy of pumps to signal and idler waves. It can be generated due to intensity fluctuations of neighboring channels. Let three waves of different frequencies f_k, f_l, f_m ($k \neq l, m$) are propagating in the same fiber. Due to the third-order electric susceptibility, they will interact with each other and a product wave will be generated at frequency $f_{klm} = f_k + f_l - f_m$. The output power of FWM (P_{klm}) is proportional to the interacting of signal powers and can be expressed as a function of [108] :

$$P(f_k + f_l - f_m) = \eta(f_k, f_l, f_m) \cdot \frac{\gamma^2}{9} d_{klm}^2 P_k P_l P_m e^{-\alpha L} \frac{(1 - e^{-\alpha L})^2}{\alpha^2} \quad \text{----(5.8)}$$

Where $P(f_k + f_l - f_m)$ represents the input peak power at the frequencies f_k, f_l, f_m , d_{klm}^2 is the degeneracy factor and $\eta(f_k, f_l, f_m)$ is the mixing efficiency of f_k, f_l, f_m frequencies. The term $\frac{1 - e^{-\alpha L}}{\alpha}$ can be expressed as effective length L_{eff} and equation (5.8) becomes

$$P(f_k + f_l - f_m) = \eta(f_k, f_l, f_m) \cdot \frac{\gamma^2}{9} d_{klm}^2 P_k P_l P_m e^{-\alpha L} L_{\text{eff}}^2 \quad \text{----(5.9)}$$

Where $\eta(f_k, f_l, f_m)$ can represent as

$$\eta = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \left\{ 1 + \frac{4 e^{-\alpha L} \sin^2\left(\frac{\Delta\beta L}{2}\right) \cdot \alpha^2}{L_{\text{eff}}^2} \right\} \quad \text{----(5.10)}$$

where $\Delta\beta$ represents the phase mismatch. Putting the value of η from equation (5.10) into equation (5.9), we get

$$P(f_k + f_l - f_m) = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \left\{ 1 + \frac{4 e^{-\alpha L} \sin^2\left(\frac{\Delta\beta L}{2}\right) \cdot \alpha^2}{L_{\text{eff}}^2} \right\} \frac{\gamma^2}{9} \cdot d_{klm}^2 P_k P_l P_m e^{-\alpha L} L_{\text{eff}}^2 \quad \text{----(5.11)}$$

For consideration of effective area (A_{eff}) of the guided mode and third order non linearity susceptibility, the final solution of equation (5.11) can be expressed as

$$P(f_k + f_l - f_m) = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \left\{ 1 + \frac{4 e^{-\alpha L} \sin^2\left(\frac{\Delta\beta L}{2}\right) \cdot \alpha^2}{L_{\text{eff}}^2} \right\} \frac{1024 \pi^6}{n^4 \lambda^2 c^2} \chi_{1111}^2 \cdot d_{klm}^2 P_k P_l P_m e^{-\alpha L} \left(\frac{A_{\text{eff}}}{L_{\text{eff}}} \right)^2 \quad \text{----(5.12)}$$

Where χ_{1111} is third order nonlinear susceptibility.

5.1.1.3 Theoretical Analysis of SRS

SRS is mainly occur due to interaction of photon with silica molecules themselves. Taking for granted, both channels are propagating optical waves randomly and independent from each other. Assuming scrambled polarization, the fractional power lost by the first channel to the nth channel [108,109]:

$$D_n = \sum_{n=1}^{N-1} 1.4 * 10^{-6} \left(\frac{\lambda_n}{\lambda_1} \right) \frac{P_i Y_n (1 - \exp(-\alpha L))}{2\alpha A_{\text{eff}}} \quad \text{----(5.13)}$$

Where N is the number of channels, P_i represents the input optical power, Y_n represents Raman gain coefficient and can be expressed as

$$Y_n = \frac{i \Delta f * 6 * 10^{-12}}{1.5 * 10^{-13}} \quad \text{----(5.14)}$$

Where Δf represents frequency spacing. Now, we can calculate the noise power by SRS

$$P_{\text{SRS}} = \sum_{n=1}^{N-1} 2.2 * 10^{-3} \exp \left(\frac{P_i Y_n L_{\text{eff}}}{2A_{\text{eff}}} - 1 \right) \quad \text{----(5.15)}$$

5.1.1.4 Theoretical Analysis of SBS

We can analyze the SBS effect with a set of coupled Ordinary Differentially Equations (ODEs) for spatial evaluation for the pump and stokes waves [110 -111].

$$\frac{dI_s}{dz} = -GI_s I_p + \alpha_s I_s \quad \text{----(5.16)}$$

$$\frac{dI_p}{dz} = -GI_p I_s - \alpha_p I_p \quad \text{----(5.17)}$$

Where I_s and I_p represents light intensity of optical signal and pump in the fiber. α_s and α_p represent fiber optic attenuation of optical signal and pump respectively. G represents Brillouin Gain Coefficient of the medium.

For estimating SBS, guided optical power can be analyzed from equations (5.16) and (5.17), after neglecting the pump depletion

$$\frac{dP_s}{dz} = -\eta GP_s P_p + \alpha_s P_s \quad \text{----(5.18)}$$

$$\frac{dP_p}{dz} = -\eta GP_p P_s - \alpha_p P_p \quad \text{----(5.19)}$$

Where η is the peak SBS efficiency and can be expressed as

$$\eta = \frac{G}{A_{\text{eff}}} \quad \text{----(5.20)}$$

and G represents the Brillouin Gain Coefficient and equals to

$$G = \frac{P_e(\Delta f_{B/2})^2}{[(f_s - f_p) - f_B]^2 + (\Delta f_{B/2})^2} \quad \text{----(5.21)}$$

Where P_e represents polarization coefficient, Δf_B is the bandwidth of Brillouin Gain, f_s, f_p, f_B are Stokes light frequency, pump wave frequency and Brillouin scattering frequency shift respectively.

5.1.1.5 Theoretical Analysis of System Model

The r. m. s. laser power at the fiber will be equal to [111, 112]:

$$P_{\text{total}} = \frac{m P_{\text{in}}}{\sqrt{2}} \quad \text{----(5.22)}$$

The photocurrent can be expressed as

$$i_q = R_o P_{\text{total}} 10^{-\alpha/10} \quad \text{----(5.23)}$$

Where R_o represents the responsivity of PIN photodiode (A/w), P_{total} is the Laser power and α is total attenuation in dB.

The parameter α depends upon various parameters like number of ONUs, fiber distribution configuration, length of the channel, properties of cross connects and other switching devices etc. Assuming these parameters constant with the time delay which can be expressed as symmetric differentiated phase around the given wavelength

$$T_d = - \frac{1}{4\pi} \frac{(w_{i+1} - w_{i-1})}{\Delta f} \quad \text{----(5.24)}$$

Where Δf is the step of frequency grip.

The r.m.s. output power at PIN photodiode can be calculated as

$$P_o = \left[\frac{R_o m P_{\text{total}} 10^{-\alpha/10}}{\sqrt{2}} \right]^2 \exp \left(\frac{1}{4\pi} \frac{(w_{i+1} - w_{i-1})}{\Delta f} \right) \quad \text{----(5.25)}$$

The Carrier to noise ratio (CNR) can be calculated as

$$(CNR)^2 =$$

$$\frac{(P_o)^2}{(\text{Noise power (XPM)})^2 + (\text{Noise power (FWM)})^2 + (\text{Noise power (SRS)})^2 + (\text{Noise power (SBS)})^2} \quad \text{----(5.26)}$$

5.1.2 System Setup

The block diagram of bidirectional hybrid PON system is shown in figure 5.1. In this system, the Optical Line Terminal (OLT) is equipped with CW laser source (at 1550 nm

wavelength and 100 MHz line width) with PRBS generator for 10 Gbps data rate. A carrier for downstream is also generated at 1310 nm wavelength as shown in the figure. To detect the upstream data, PIN photodiode (with 1A/W responsivity, zero ampere dark current, thermal noise of 10^{-11} A/ $\sqrt{\text{Hz}}$) is used with Bessel filter. Various analyzers are also employed for calculating BER and other measuring parameters. A bidirectional fiber link (with 0.25 dB/km attenuation and 16.75 ps/nm/Km dispersion) of varying length is employed to communicate between OLT and ONUs. The signals are modulated with Mach-Zehnder modulator (with 30 dB extinction ratio). The optical signals from fibers are sent through two remote nodes. At remote node 1, passive splitter and combiner (with coupling factor of 0.50) are used for coupling number of wavelengths and data is further sent to number of ONUs using power splitters and combiners with 10 ps time delay.

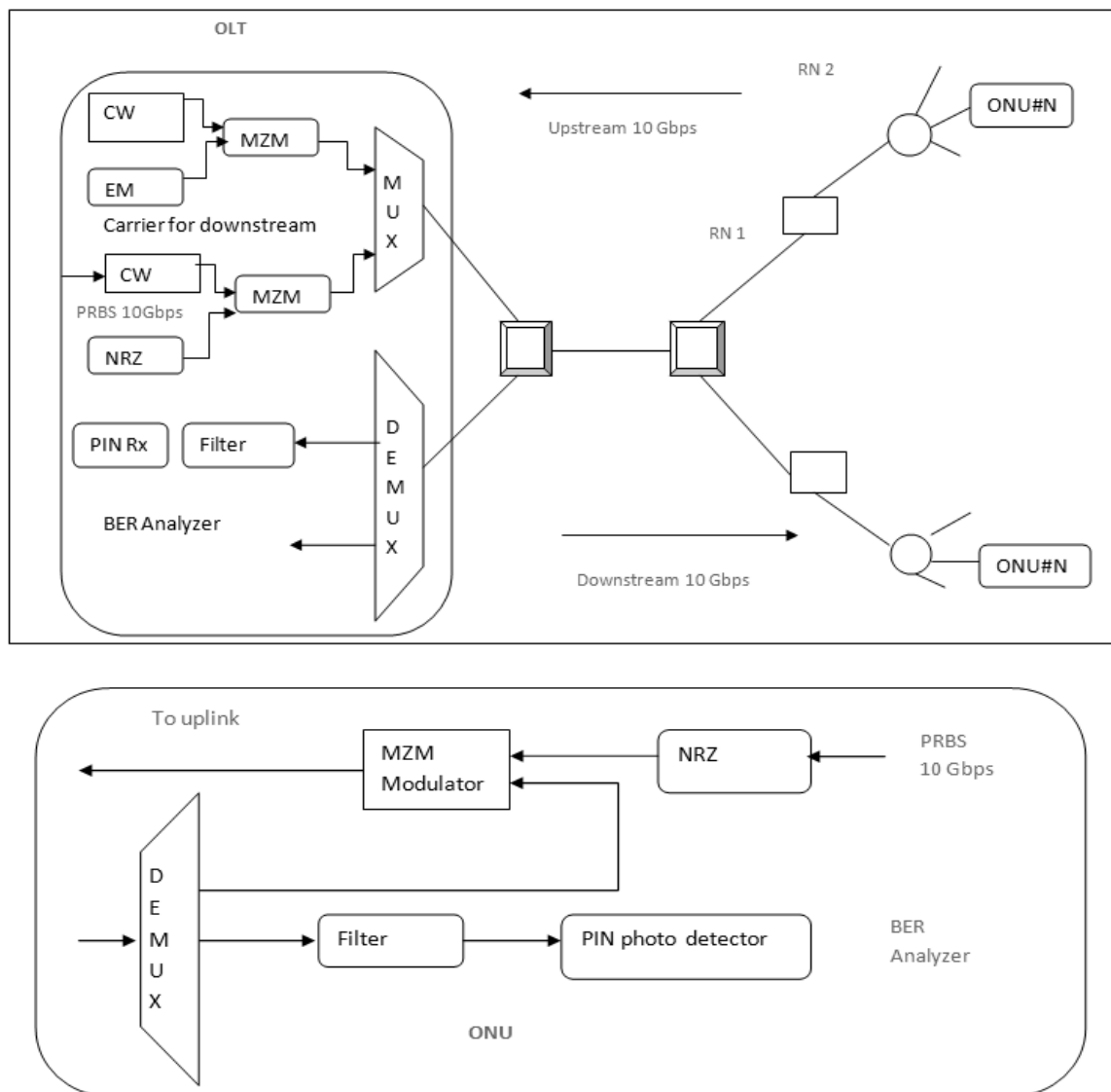


Figure 5.1: Block diagram of bidirectional hybrid (WDM/ TDM) PON system

At the ONU, the downstream signal is passed through De-multiplexer and then recovered by Bessel filter and PIN photodiode. For the upstream signal, 10 Gbps data is generated through PRBS generator and carrier is used from the OLT through demultiplexer and modulated with MZM modulator.

5.1.3 Result and Discussion

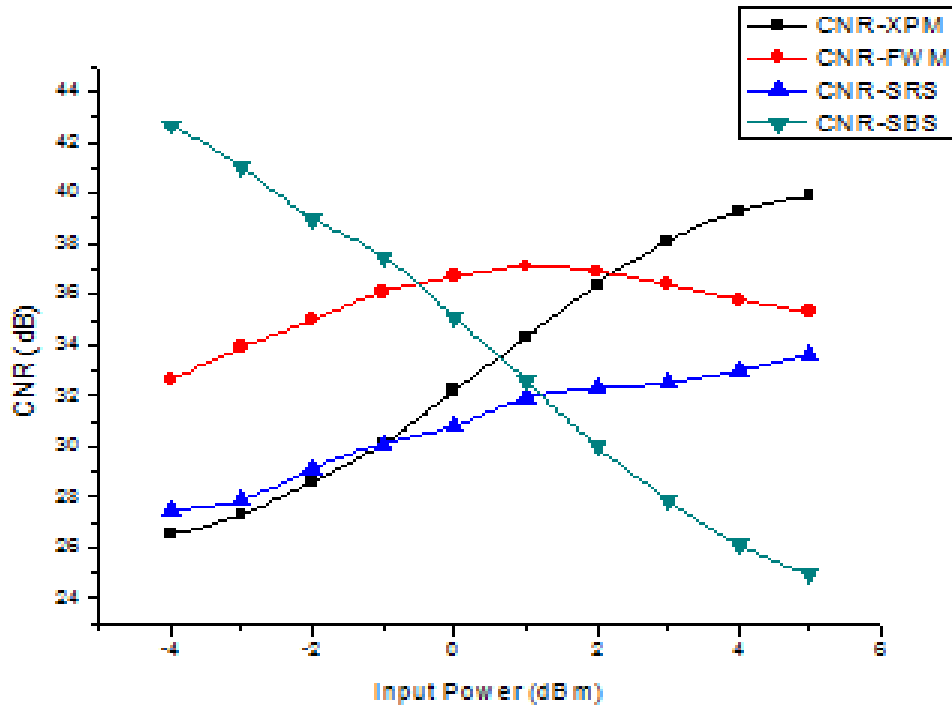
In order to observe the performance of proposed hybrid PON system in the presence of crosstalk due to fiber nonlinearities like XPM, FWM, SRS and SBS, the following values are assumed as given in table 5.1.

Table 5.1: Various parameters used for nonlinear crosstalk effects

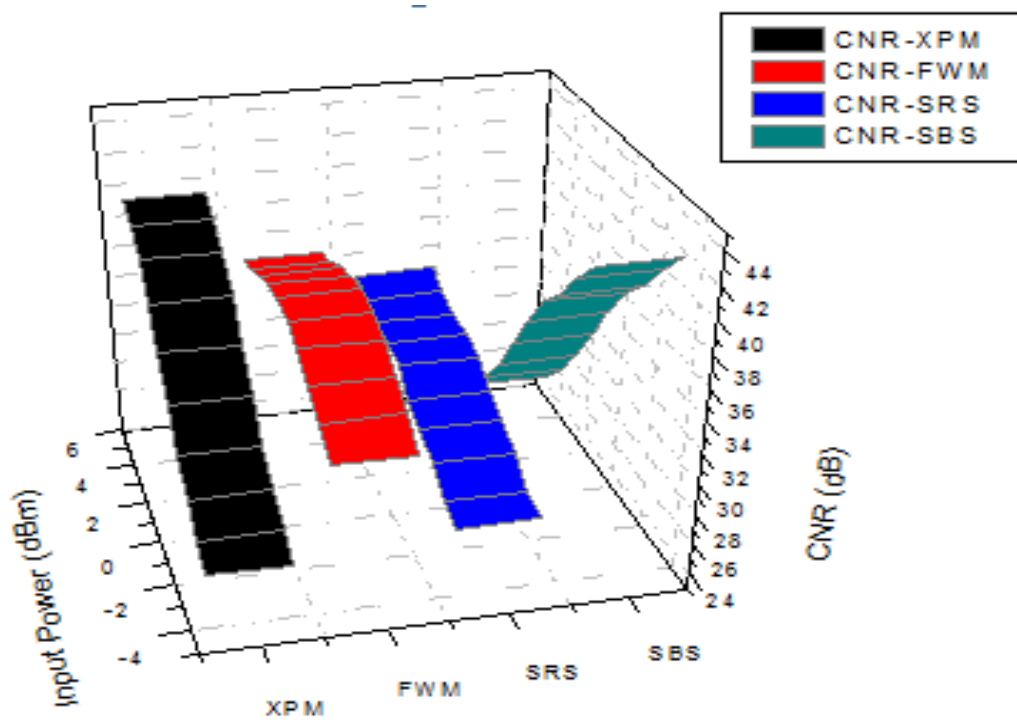
Sr. No.	Parameters	Values
1	Fiber Loss (α)	0.25 dB/Km
2	Optical wavelength (λ_1)	1550 nm
3	Optical wavelength (λ_2)	1310 nm
4	Frequency spacing	4nm
5	Quantum efficiency of Photo detector	0.95
6	Raman Gain Profile	$7 \times 10^{-12} \text{ cm/w}^2$
7	Bandwidth	10 Ghz
8	Insertion loss coupler	0.5 dB
9	Splice loss	0.5 dB
10	Receiver temperature	300 K
11	Electrical Bandwidth of receiver	1 Ghz
12	Spontaneous Emission Factor	3
13	Dispersion slop	$0.075 \text{ ps/nm}^2 \cdot \text{km}$
14	A_{eff}	80 um^2
15	Non linear index coefficient	2.6×10^{-20}
16	Data Rate	10 Gbps

A plot for CNR for the proposed system with respect to input power as a function of different nonlinearities in 2D and 3D is shown in figure 5.2. It is observed that CNR varies from (26.5 to 39.9) dB with induced XPM. The effect of XPM is decreasing with the increase in input power. It varies from (32.6 to 37.1) dB with FWM at low input power but again, it decreases up to 35.3 dB at high input power. The SRS dominates more

at low input power and CNR varies from (27.5 to 33.6) dB. The effect of SBS increases with respect to input power and CNR varies from (42.7 to 24.9) dB under the influence of SBS.



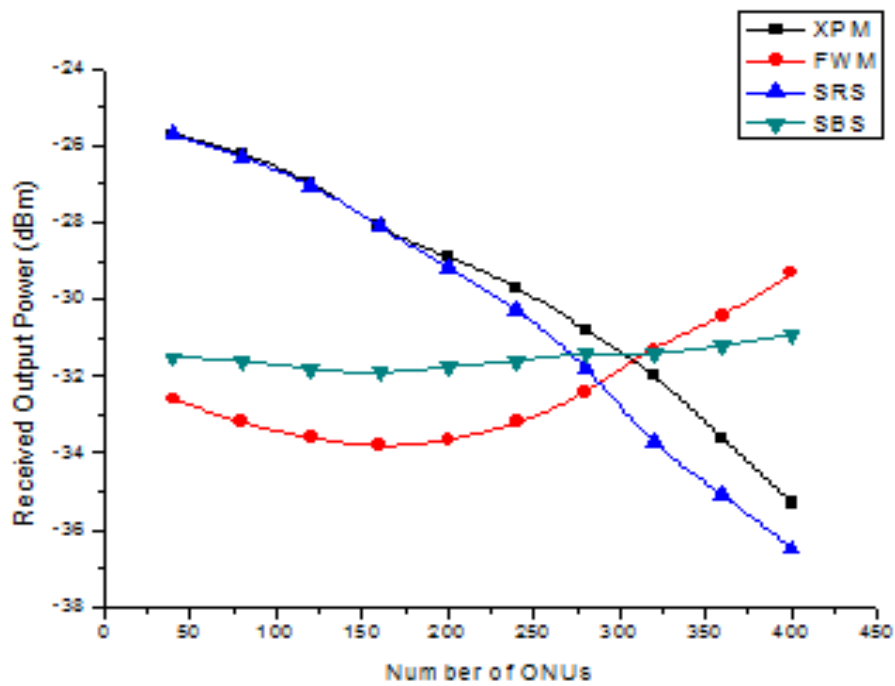
(a)



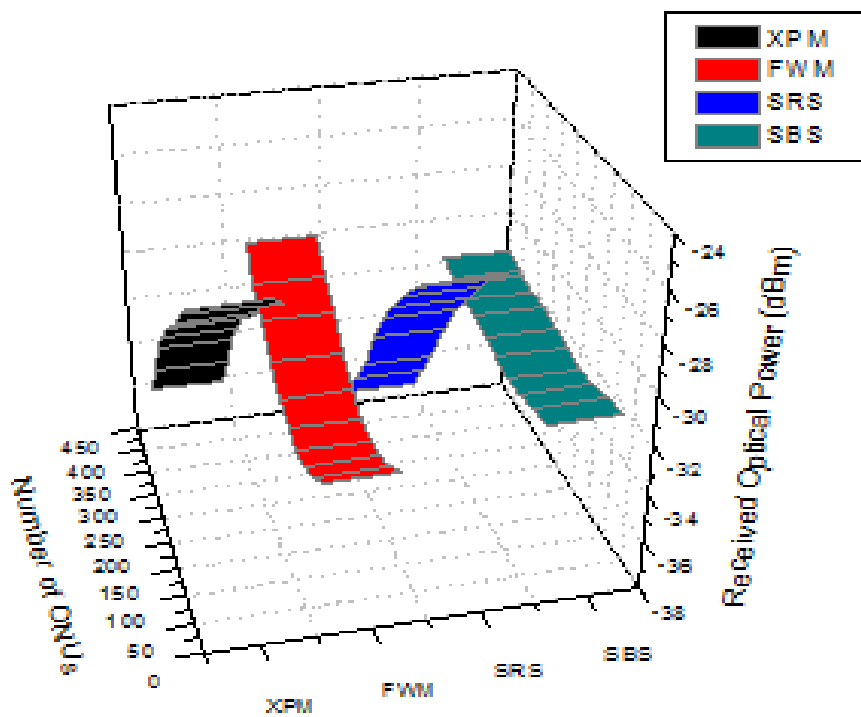
(b)

Figure 5.2: CNR versus input power for various nonlinearities in (a) 2D and (b) 3D

The received output power with respect to number of ONUs under the influence of nonlinearities in 2D and 3D is shown in figure 5.3.



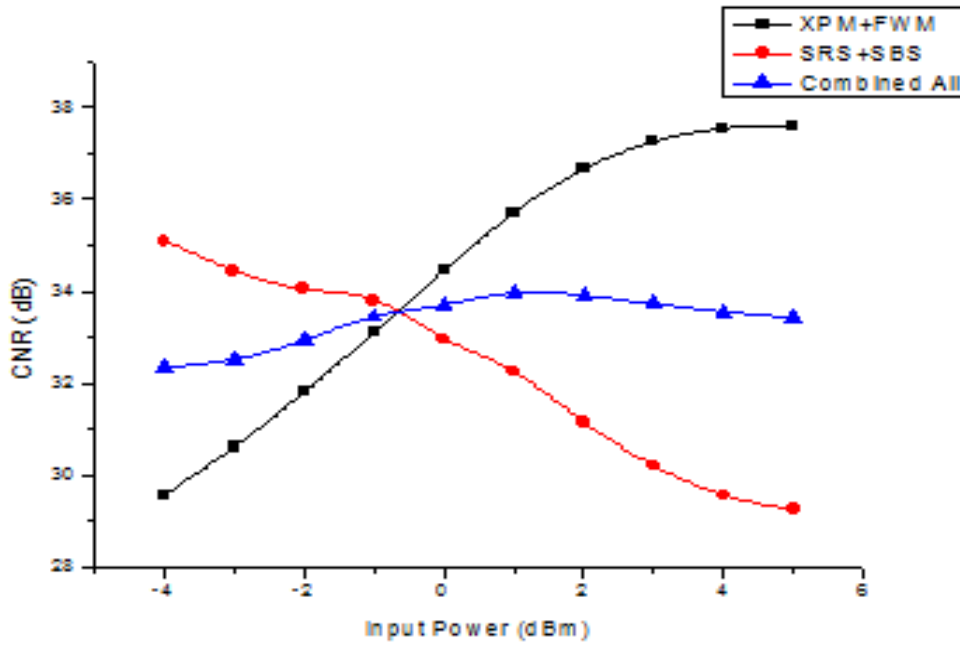
(a)



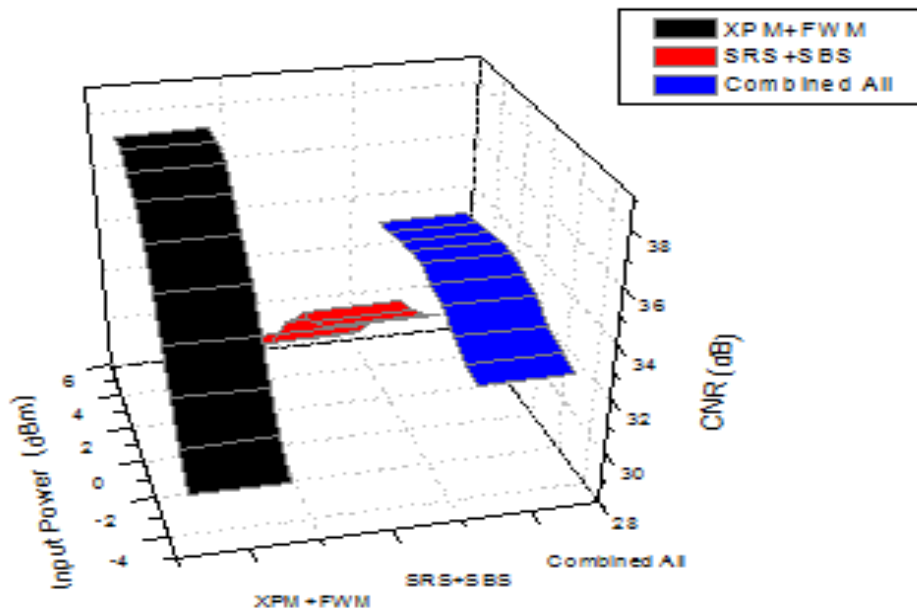
(b)

Figure 5.3: The received power versus number of ONUs for various nonlinearities in (a) 2D and (b) 3D

It is evident that the received output power decreases due to increase in the number of ONUs. With the effect of nonlinearities, it is observed that the power varies from (-25.7 to -35.3) dBm with induced XPM. It varies from (-32.6 to -36.58) dBm with FWM and from (-25.7 to -36.5) dBm with SRS and from (-31.5 to -30.9) dBm with SBS effect.



(a)



(b)

Figure 5.4: CNR versus input power for combined effect of various nonlinearities in (a) 2D and (b) 3D

The combined effect of various nonlinearities at CNR in 2D and 3D is shown in figure 5.4. It is evident that CNR varies from (29.55 to 37.6) dB with combination of XPM and FWM effect and from (35.1 to 29.25) dB with combination of SRS and SBS effects and from (-32.3 to 33.4) dB under the influence of all these nonlinearities. The effect of various nonlinearities at BER with respect to input power is shown in figure 5.5.

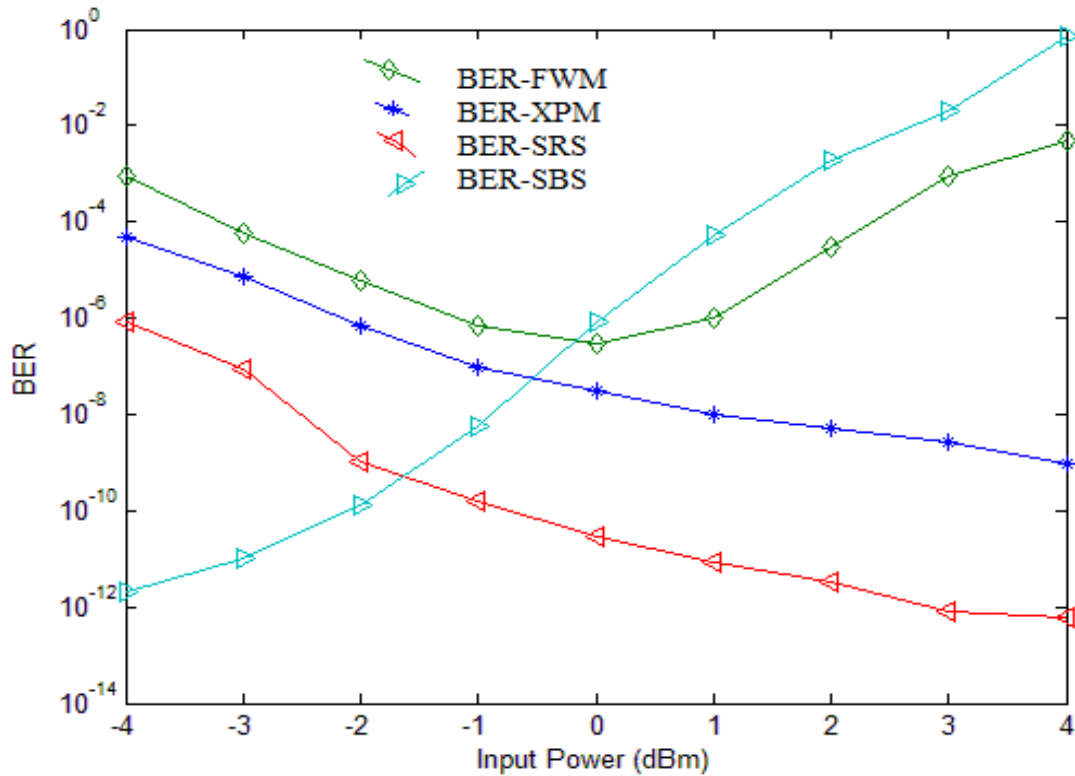


Figure 5.5: BER versus input power for various nonlinearities

It is evident that SBS becomes the most dominant nonlinearity at high input power and it limits the desired high launched power for long transmission and the number of ONUs. These effects of nonlinearities should be neutralized with suitable precautions.

5.2 Analysis and Mitigation of XPM Crosstalk in MLRs with Multi Channel Spacing

The demand of volume of traffic in the next generation access networks brings up various design issues for supporting high data rate, large bandwidth requirement, enhanced security and scalability for the future applications [90]. Hybrid PONs with different multiplexing techniques like WDM, TDM and Code Division Multiple Access (CDMA) etc. are shown as a prominent solution to provide a cost-effective and scalable network to prop up the rising heterogeneity of traffic demands by having MLRs over number of

channels for all the end subscribers [113]. Due to propagation of number of channels in the same fiber and the increase in the channel bit rate, nonlinear impairments dominate the performance.

As per the literature survey, various architectures of PON have been investigated as shown in table 2.1. But the necessity of heterogeneities in the data rate and channel spacing is not achieved yet. In this section, we have proposed a network with multi data rates at different channel spacing which have better results than conventional uniform channel spacing networks. Through this model, we can provide a flexible network to the end users in terms of data rate, bandwidth, channel spacing etc. as per their demand.

5.2.1 Theoretical Analysis

To improve the system performance, it is important to analysis the nonlinear effects (like Kerr nonlinearities) in optical network. These effects rise to interference, losses, distortion and degradation of the output signals. In this section, we have discussed the effect of XPM crosstalk on the network. The XPM is the result of phase inflection of the optical field originated by another optical signal propagating within the same fiber and can be analyzed using Non Linear Schrodinger Equation (NLSE). Considering an optical signal $A(t, z)$ propagating in the fiber [106, 107]:

$$\frac{\partial A(t,z)}{\partial z} + \frac{\alpha_1}{2} A_1(t,z) + \frac{i}{2} \beta_{21} \frac{\partial^2 A_1(t,z)}{\partial T^2} - \frac{1}{6} \frac{i\beta_{31} \partial^3 A_1(t,z)}{\partial T^3} = i\gamma [9 |A_1|^2 |A_2|^2 |A_3|^2] A_1(t,z) + \Psi_\omega$$

----(5.27)

Where β_{in} is dispersion parameter, α_n is the optical attenuation in the nth channel and (γ) is the channel's non linearity coefficient. The final solution of this equation for power with XPM crosstalk effect can be expressed as:

$$|P(\omega, L)| = 8 \pi \gamma P_j(o) P_k(\omega) e^{-\alpha L} \left\{ \frac{\sin(\beta\omega^2/2)}{\beta\Delta\lambda\omega} \right\}$$

----(5.28)

The calculated results are shown in Table 5.2 & 5.3 in the results and discussion section with simulative results.

5.2.2 System Setup

In the proposed system, we focus on the analysis of nonlinear crosstalk caused by XPM in PONs for MLRs i.e. 10/ 20/ 40 Gbps. Further, the two schemes (i) uniform channel spacing, (ii) mixed channel spacing for MLRs are discussed for the proposed network. The schematic of the proposed network is shown in figure 5.6. In this system, three CW

laser sources (tuned at 1310 nm, 1490 nm and 1550 nm wavelength) with different Pseudo Random Bit Sequence (PRBS) of 10, 20 and 40 Gbps are employed at the Optical Line Terminal (OLT) end respectively. Non Return to Zero (NRZ) format is used as line coding. The signals are further modulated by Mach-Zehnder Modulator (MZM) with 30 dB extinction ratio and combined through WDM multiplexer. Semiconductor Optical Amplifier (SOA) with 3 dB gain is used to boost up the signals to the channel.

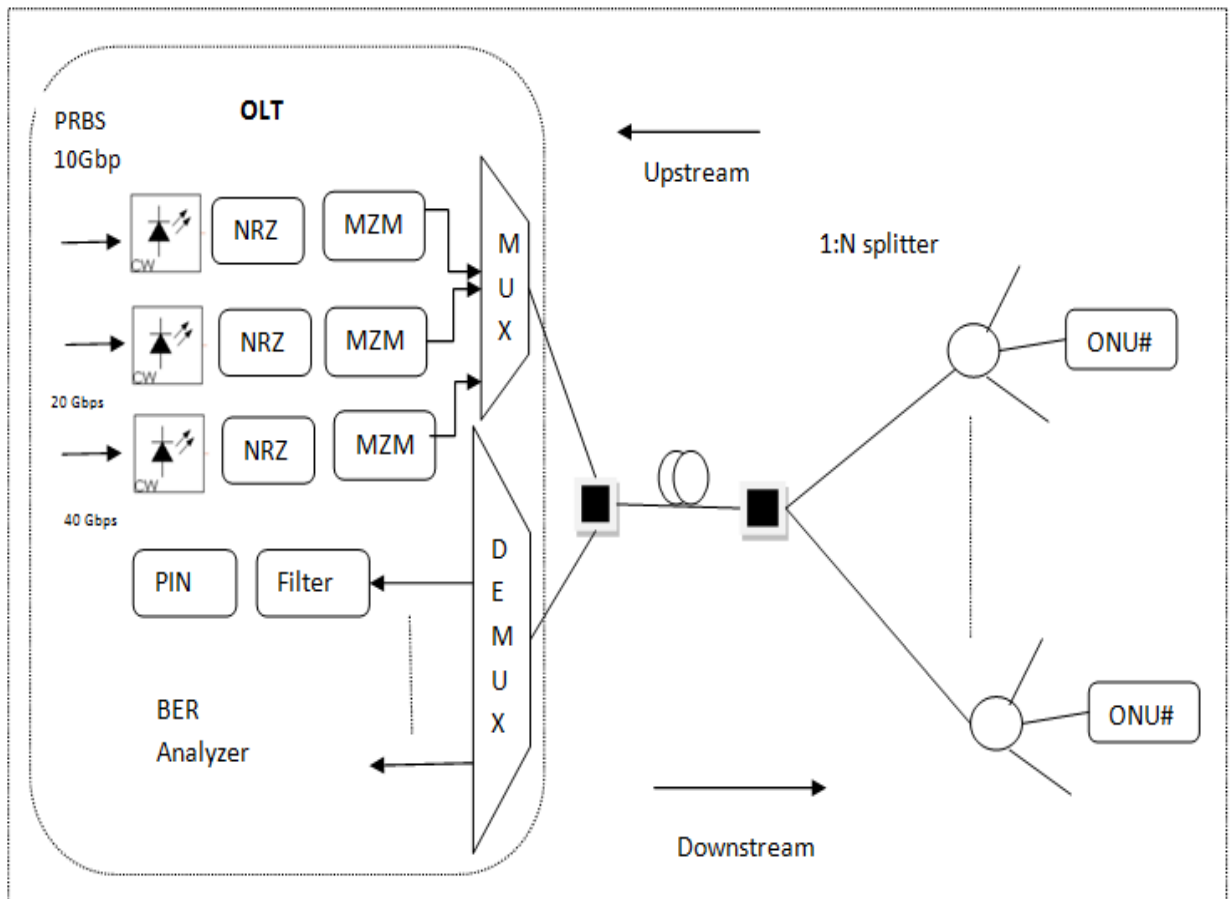


Figure 5.6: Schematic of proposed bidirectional PON system

A fiber link (with 0.2 dB/Km attenuation and 16.75 ps/nm/Km dispersion) of 60 Km length is installed in the channel. To detect the upstream data, PIN photodiode (1A/W responsivity, zero ampere dark current, and thermal noise of 10^{-11} A/ $\sqrt{\text{Hz}}$), a demultiplexer and Bessel filter are used. Further, the signal is transmitted through twenty one optical splitters and combiners (with 1x4 ratios and coupling factor 0.50). All of these signals travel through another 1 Km fiber (with different time delay parameters) to reach 64 number of ONUs. For sharing of these wavelengths in different time slots, 10 ps time delay is given to each ONU through power splitter module to receive the signal i.e. the

signal will reach at first ONU with zero time delay and at second ONU with 10 ps delay and so on. The block diagram of ONU is shown in figure 5.7.

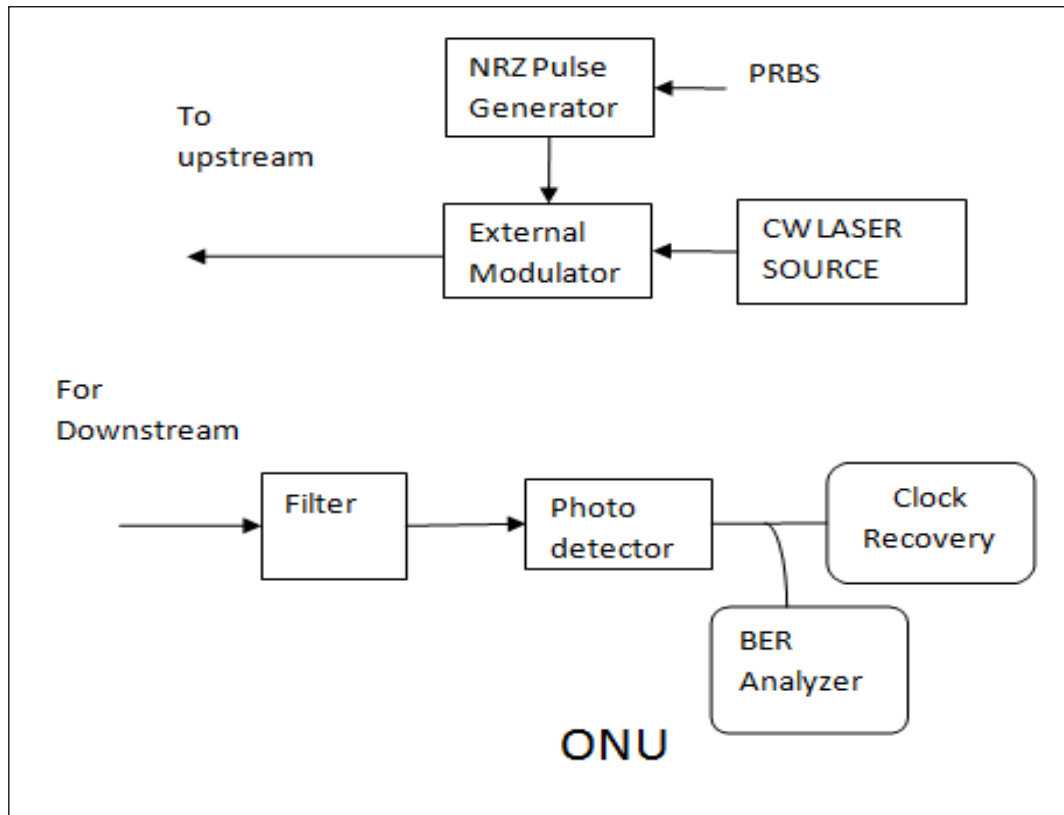
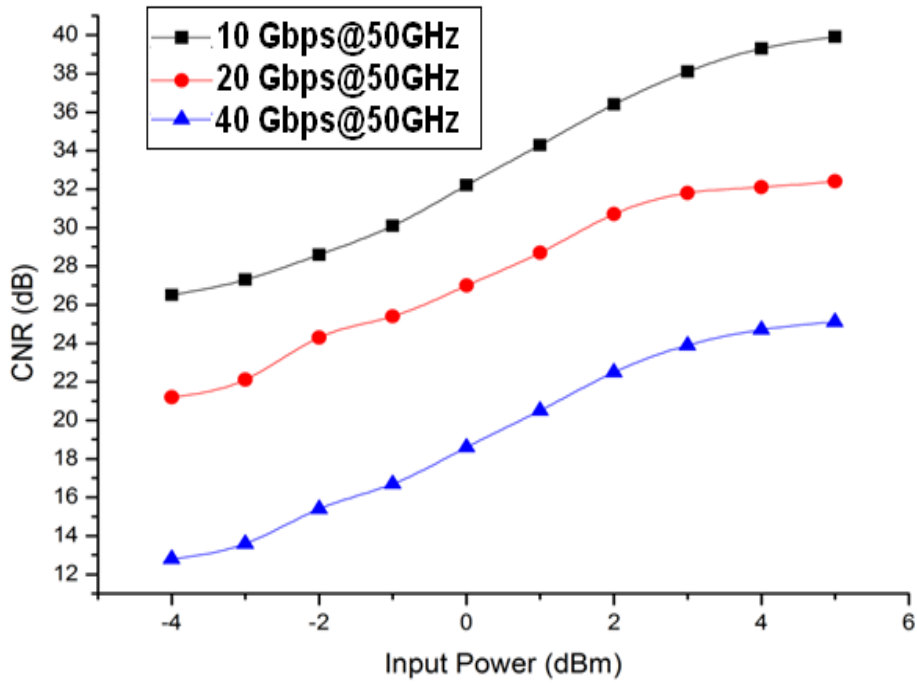


Figure 5.7: Block diagram of ONU

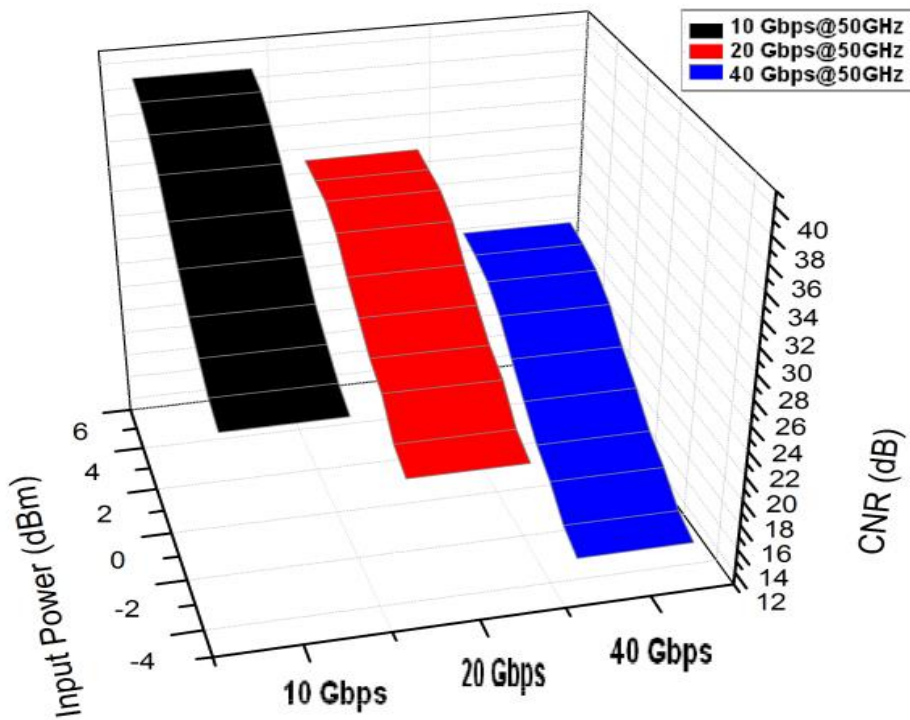
The downlink signal is decoded using PIN photodiode with Bessel's filter. A clock recovery is also associated to perform synchronized detection. To upload the data to central office, PRBS at 2.5 Gbps data rate with NRZ coder and CW laser source (890 nm wavelengths) are used. Various analyzers are also used for observing the received power, CNR etc. The setup is simulated in VPI Transmission Maker 8.7 software and results have been discussed in the next section.

5.2.3 Result and Discussion

The system is investigated for nonlinear crosstalk caused by XPM with MLRs i.e. 10/ 20/ 40 Gbps for uniform channel spacing (at 50 GHz) and mixed channel spacing (at 20, 50 & 100 GHz with respect to 10, 20 & 40 Gbps respectively). CNR versus input power for MLRs at uniform spacing (in 2D and 3D) is shown in figure 5.8.



(a)

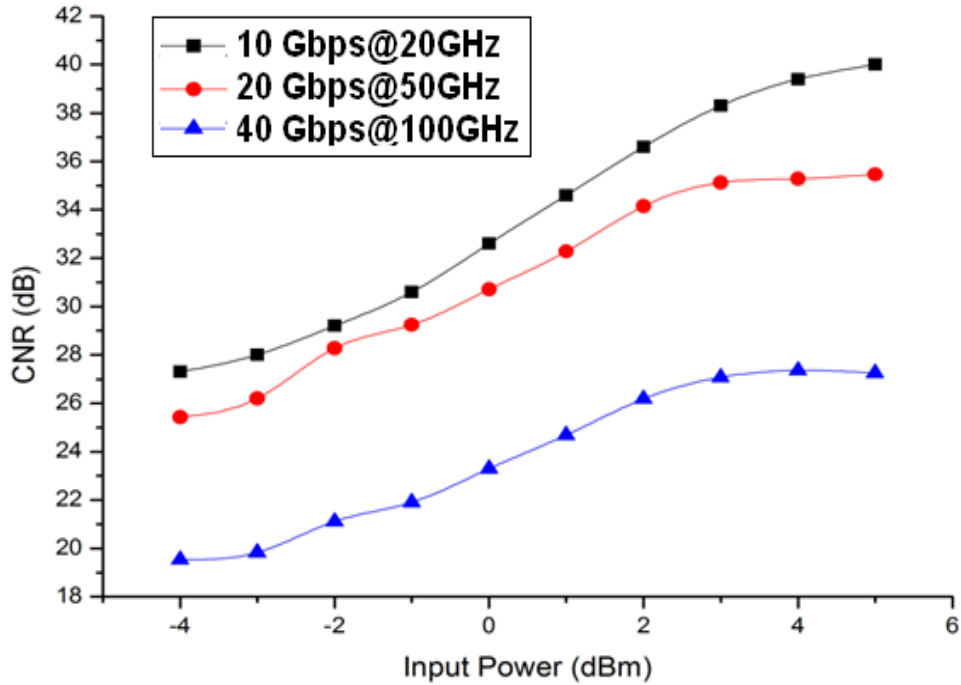


(b)

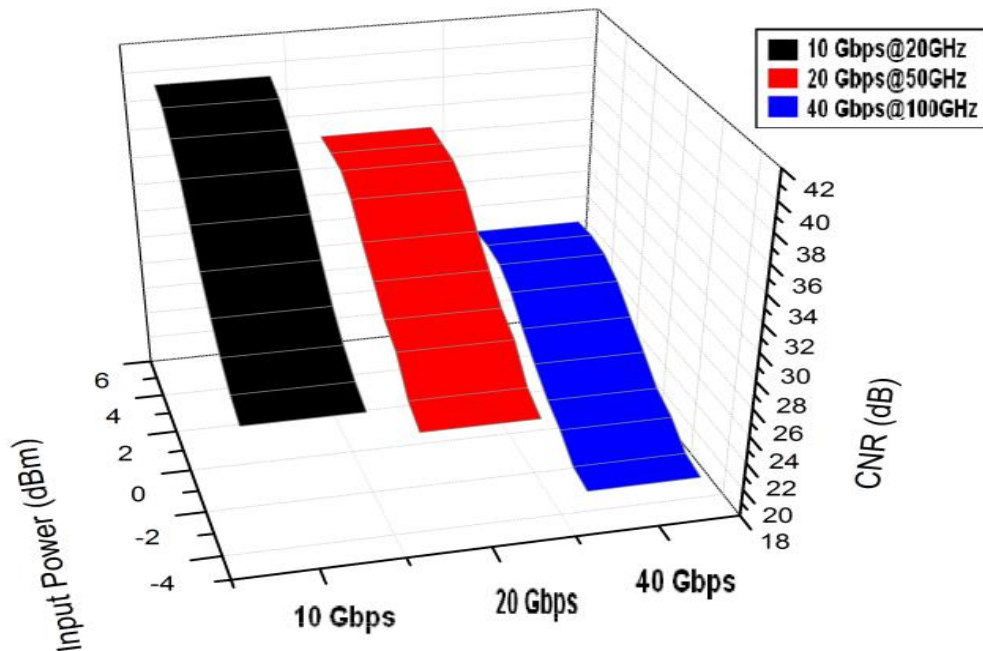
Figure 5.8: CNR versus input power for mixed line rates at uniform spacing in (a) 2D and (b) 3D

The system is simulated at 50 GHz channel spacing for all line rates. The CNR of 26.5 to 39.9 dB, 21.2 to 32.4 dB and 12.8 to 25.1 dB are observed with 10, 20 and 40 Gbps of

speed respectively. It is observed that CNR is increasing with increase in input power. Also, it is shown that CNR is varying with the different line rates. We get better CNR in case of 10 Gbps than higher line rates. 20 Gbps line rate shows moderated CNR. CNR versus input power for MLRs at mixed spacing is shown in figure 5.9.



(a)



(b)

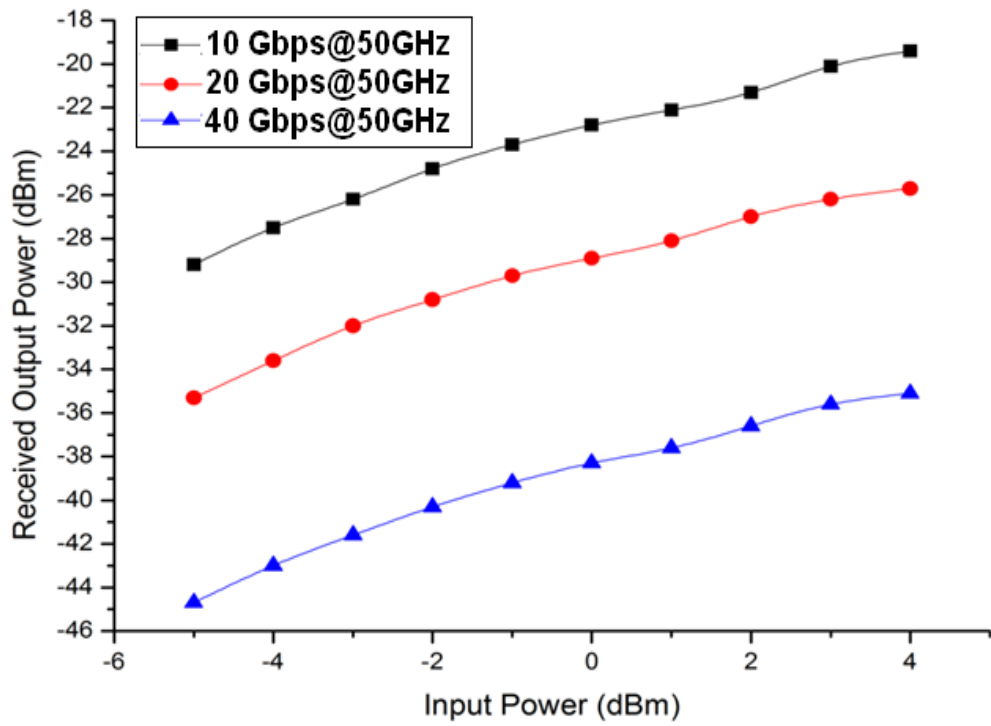
Figure 5.9: CNR versus input power for mixed line rates at mixed spacing in (a) 2D and (b) 3D

Further, the setup is simulated at 20 GHz, 50 GHz and 100 GHz channel spacing for 10 Gbps, 20 Gbps and 40 Gbps line rates respectively. The CNR of 27.3 to 40 dB, 25.43 to 35.46 dB and 19.54 to 27.25 dB with 10, 20 and 40 Gbps is observed due to induced XPM respectively. It is evident that the system performance is improved by using mixed channel spacing instead of uniform channel spacing. The calculated CNR for different line rates with uniform and mixed spacing with respect to input power is given in Table 5.2.

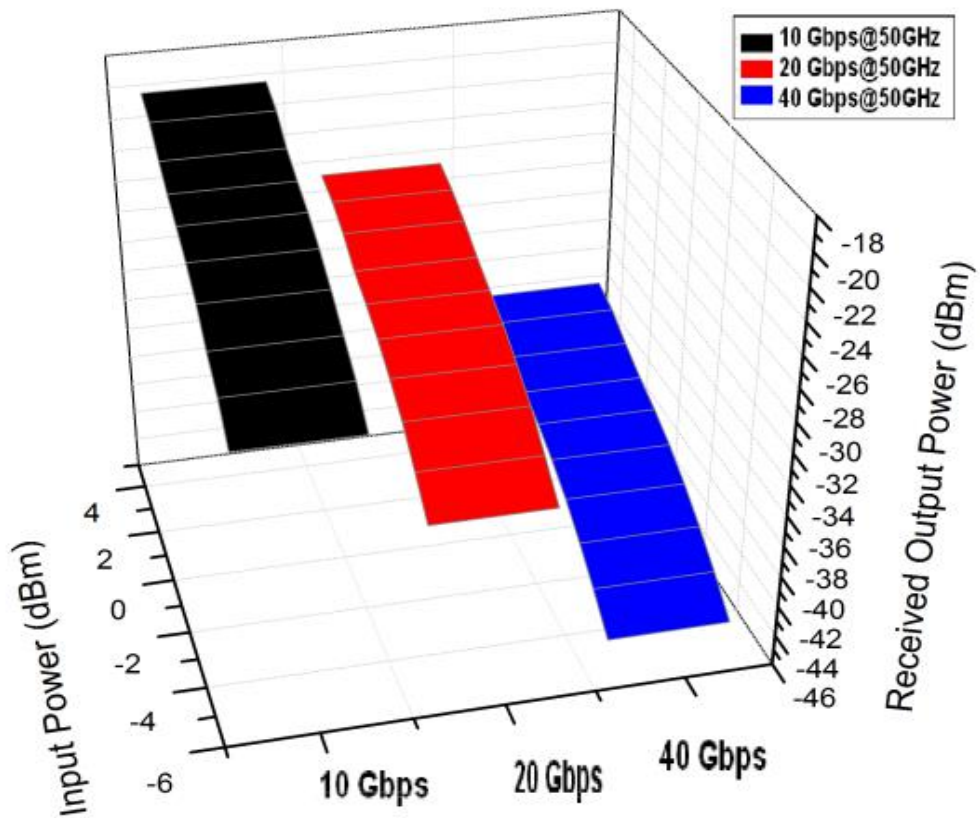
Table 5.2: CNR for mixed line rates with uniform and mixed spacing versus input power

Input Power (dBm)	CNR at Uniform Channel Spacing (dB)			CNR at Mixed Channel Spacing (dB)		
	10 Gbps @ 50 Ghz	20 Gbps @ 50 Ghz	40 Gbps @ 50 Ghz	10 Gbps @ 20 Ghz	20 Gbps @ 50 Ghz	40 Gbps @ 100 Ghz
-4	26.5	21.2	12.8	27.3	25.43	19.54
-3	27.3	22.1	13.6	28	26.2	19.83
-2	28.6	24.3	15.4	29.2	28.27	21.12
-1	30.1	25.4	16.7	30.6	29.24	21.91
0	32.2	27	18.6	32.6	30.71	23.3
1	34.3	28.7	20.5	34.6	32.28	24.69
2	36.4	30.7	22.5	36.6	34.15	26.18
3	38.1	31.8	23.9	38.3	35.12	27.07
4	39.3	32.1	24.7	39.4	35.29	27.36
5	39.9	32.4	25.1	40	35.46	27.25

Due to combination of all the different line rates at the channel (as shown in system setup), the observed CNR is different for same line rate and channel spacing (e.g. 20Gbps@50GHz) between the uniform spacing case and the mixed spacing case. As the various effects such as crosstalk, power transient and other non linearity are depending on the channel spacing [113]. It directly affects the CNR. The mixed channel spacing reduces these effects and high CNR is observed. Received output power versus input power for Mixed Line Rates at uniform spacing (in 2D and 3D) is shown in figure 5.10.



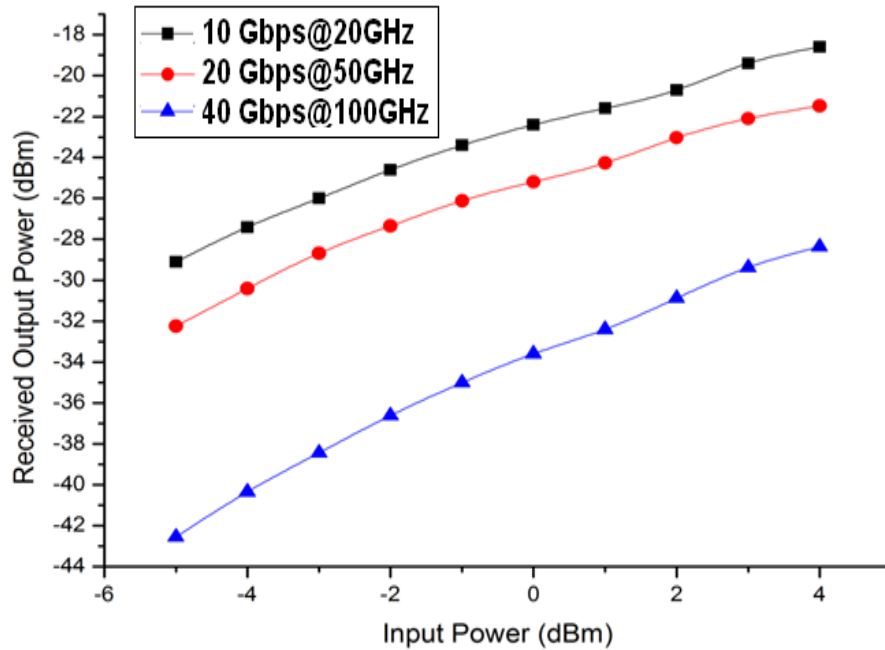
(a)



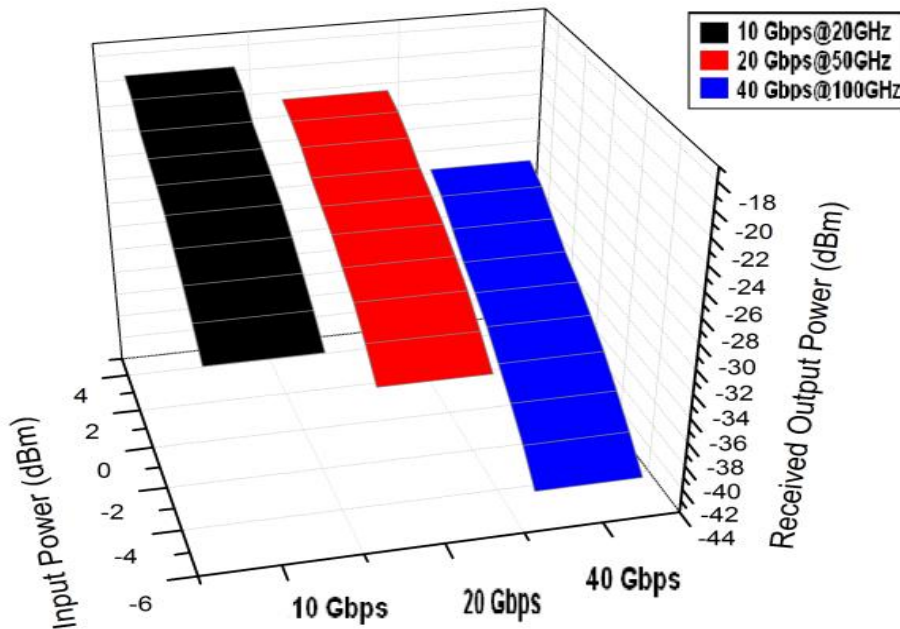
(b)

Figure 5.10: Received output power versus input power for mixed line rates at uniform spacing in (a) 2D and (b) 3D

It is observed that the received output power increases due to increase in the input power. The Output power varies from (-29.1 to -18.6) dBm with 10 Gbps, from (-32.2 to -21.4) dBm with 20 Gbps and (-42.5 to -28.3) dBm with 40 Gbps at uniform channel spacing i.e. at 50 GHz. Received output power versus input power for MLRs at mixed channel spacing (in 2D and 3D) is shown in figure 5.11.



(a)



(b)

Figure 5.11: Received output power versus input power for mixed line rates at mixed channel spacing in (a) 2D and (b) 3D

The output power varies from (-29.2 to -19.4) dBm with 10 Gbps, from (-35.3 to -25.7) dBm with 20 Gbps and (-44.7 to -35.1) dBm with 40 Gbps at 20 GHz, 50 GHz and 100 GHz channel spacing due to induced XPM respectively. It is also observed that the received output power is different for same line rate and channel spacing in case of mixed channel spacing and uniform channel spacing. We have better received output power in mixed channel spacing than conventional uniform channel spacing as it reduces the overall effect of non linearity. The calculated output power for different line rates with uniform and mixed spacing with respect to input power is given in Table 5.3.

Table 5.3: Output power for mixed line rates with uniform and mixed spacing versus input power

Input Power (dBm)	O/P Power at Uniform Channel Spacing (dBm)			O/P Power at Mixed Channel Spacing (dBm)		
	10 Gbps	20 Gbps	40 Gbps	10 Gbps	20 Gbps	40 Gbps
-5	-29.2	-35.3	-44.7	-29.1	-32.24	-42.55
-4	-27.5	-33.6	-43	-27.4	-30.41	-40.34
-3	-26.2	-32	-41.6	-26	-28.68	-38.43
-2	-24.8	-30.8	-40.3	-24.6	-27.35	-36.62
-1	-23.7	-29.7	-39.2	-23.4	-26.12	-35.01
0	-22.8	-28.9	-38.3	-22.4	-25.19	-33.6
1	-22.1	-28.1	-37.6	-21.6	-24.26	-32.39
2	-21.3	-27	-36.6	-20.7	-23.03	-30.88
3	-20.1	-26.2	-35.6	-19.4	-22.1	-29.37
4	-19.4	-25.7	-35.1	-18.6	-21.47	-28.36

The three different line rates are associated with used WDM signals tuned at different wavelengths. The output power is measured with respect to these wavelengths at different channels. This is the reason that output power is observed different for different line rates. It is evident that the received output power is better for mixed channel spacing than uniform channel spacing. It is also observed that received output power is increasing with the increase in input power. BER versus input power for MLRs at uniform spacing is shown in figure 5.12.

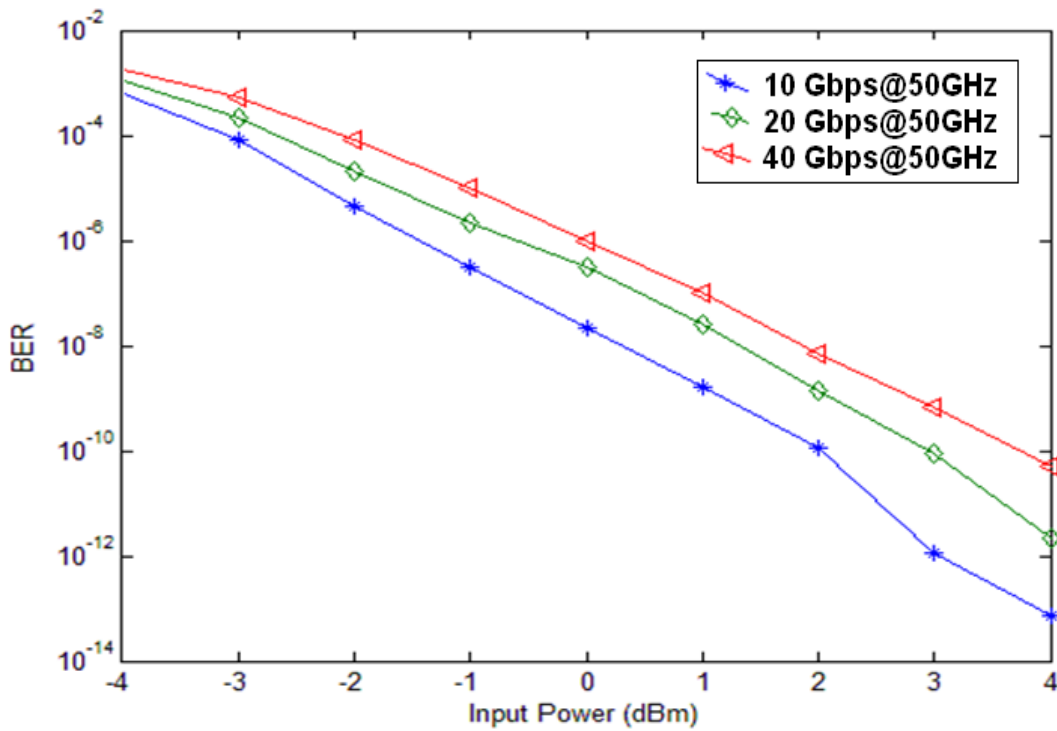


Figure 5.12: BER versus input power for mixed line rates at uniform spacing

BER is observed for the system by simulating at 50 GHz channel spacing for all line rates. BER of (7.4×10^{-14} to 6.1×10^{-4}) with 10 Gbps, (from 2.1×10^{-12} to 1.1×10^{-3}) with 20 Gbps and (from 4.9×10^{-11} to 1.8×10^{-3}) with 40 Gbps is achieved due to induced XPM respectively. It is also shown that BER decreases with the increase in input power. BER versus input power for MLRs at mixed channel spacing is shown in figure 5.13.

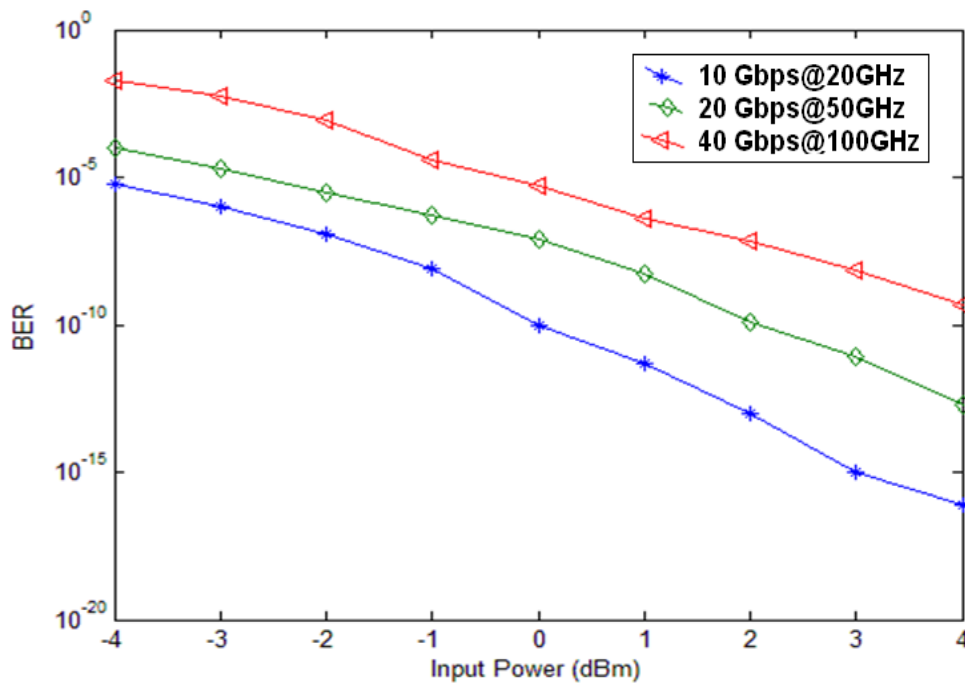


Figure 5.13: BER versus input power for mixed line rates at mixed channel spacing

BER is observed for the system by simulating at 20 GHz, 50 GHz and 100 GHz channel spacing for 10 Gbps, 20 Gbps and 40 Gbps line rates respectively. BER of (7.3×10^{-17} to 6×10^{-6}) with 10 Gbps, from (2×10^{-13} to 1×10^{-4}) with 20 Gbps and from (5×10^{-10} to 2×10^{-2}) with 40 Gbps is achieved due to induced XPM respectively. It is also shown that BER decreases with the increase in input power. It is evident that the system gives better performance in terms of BER at mixed channel spacing instead of uniform channel spacing.

5.3 Conclusion

The system has been analyzed theoretically in the presence of crosstalk due to fiber nonlinearities like XPM, FWM, SRS & SBS. The network has been expanded due to simple construction of the ONU using CCAONUs technique. Different wavelengths for downstream and upstream i.e. 1550 nm and 1300 nm have been used to mitigate the crosstalk effect of same wavelength in the same fiber respectively. Various results of CNR, input power, received output power, BER, number of ONUs in 2D and 3D have been shown with the impact of these nonlinearities. It has been found that due to these fiber nonlinearities, the system performance was affected in terms of desired launched power, expansion of the network, number of ONUs, distance etc. Further, we have designed network for Mixed Line Rates (MLRs) i.e. 10/ 20/ 40 Gbps to reduce the crosstalk. Two schemes viz. uniform channel spacing (50 GHz channel spacing to all data rates) and mixed channel spacing (20 GHz for 10 Gbps, 50 GHz for 20 Gbps and 100 GHz for 40 Gbps) have been discussed and analyzed for MLRs. It has been found that mixed channel spacing gives better performance than uniform channel spacing.

Chapter 6

Design of High Capacity HPON using Different Topologies

In this chapter, we have reported the fourth objective of the thesis i.e. to design and characterize hybrid Passive Optical Network (PON) using different topologies. Firstly, we have proposed a PON system using ring topology. Sixteen Optical Add Drop Multiplexers (OADMs) are used to make the ring network for 1500 Km distance. The network is investigated for various channel spacing and data rates. The system is further enhanced for 1024 number of users with hybrid (ring-tree) topology form using sixteen OADMs and one hundred forty four star hubs (1x8). 10 Gbps data is successfully transmitted up to 1500 Km transmission distance. The performance of the system is analyzed in terms of Q factor at various nodes with different data rates, channel spacing and pump powers. Further, a cost effective fault protection scheme is proposed for hybrid passive optical network using ring topology. Various nodes are connected in a way that they can communicate in the case of any failure in the ring network through the same fiber. So, this scheme provides the full fault protection to passive optical network system without installing extra fiber. This chapter is organized in three sections. In section 6.1, a ring network based hybrid PON is proposed. The system using hybrid topologies is described in section 6.2. Finally, a fault protection scheme is proposed in section 6.3.

6.1 Ring Network

As the need of higher capacity and long haul unrepeated transmission distance increases, the advent transmission methods have to be investigated to full-fill the demand of current technology. In reconfigurable metro networks, the transience phenomenon is present due to sudden change in overall power during add-drop operation. Because of this add-drop process, a robust deviation is present in the OADMs, which possibly reduces the Quality and BER performance. Lei Shi et al. [78] proposed PON system based on Arrayed Waveguide Grating (AWG). They have analyzed ring and tree architectures of PON system for wavelength allocation scheme with the help of a mathematical model. Stamatios V. Kartalopoulos et al. [79] investigated hybrid (CWDM/ TDM) PON using ring topology with 200 GHz channel spacing. The performance of proposed system was analyzed for eighteen channels up to 8 Km distance. As per the literature survey, the proposed models using ring network are implemented for a very less number of ONUs,

data rates and up to very short distance. The capacity of a hybrid PON can be improved with cost effective topologies. In this section, we have investigated the performance of PON with sixteen OADM in a ring topology. 10 Gbps data is successfully transmitted up to 1500 Km transmission distance.

6.1.1 System Setup

The block diagram of proposed ring topology based Passive Optical network (PON) using OADM is shown in figure 6.1. Sixteen OADM are used to receive and transmit the data with four channels at 193.1 THz center frequency with 100 GHz channel spacing between the nodes. Distance between each OADM is kept 100 Km, so, total 1500 Km transmission distance is achieved.

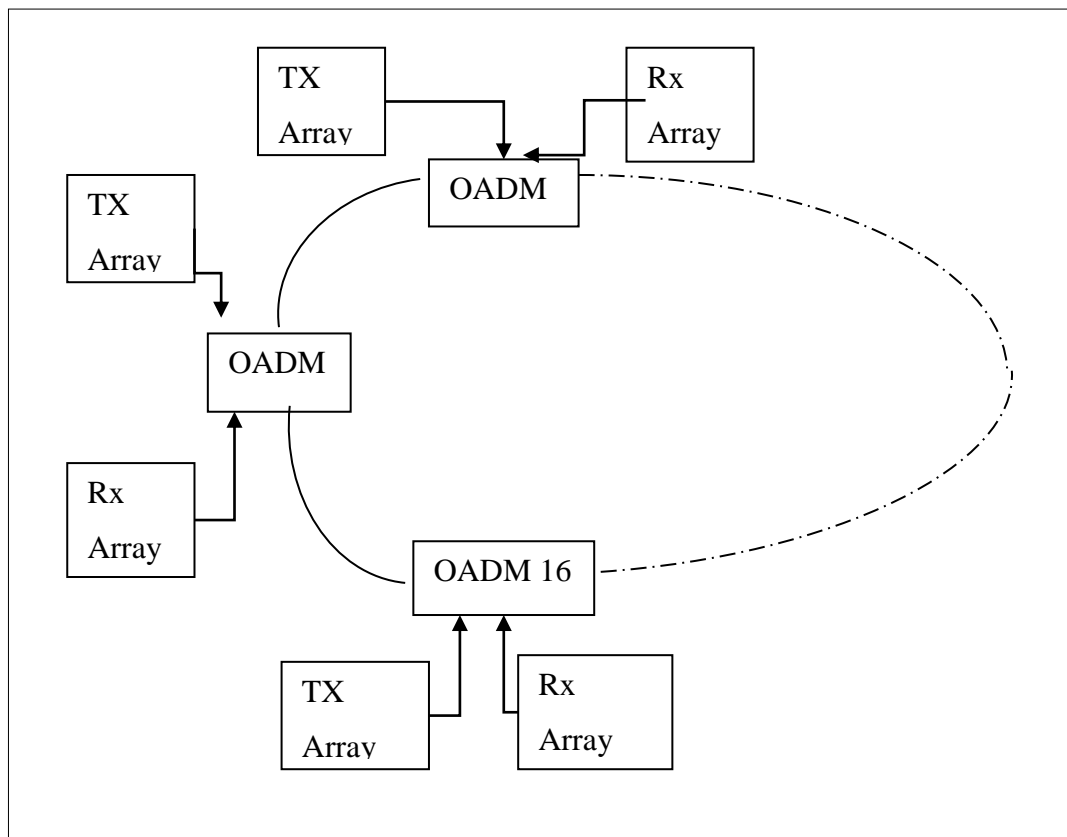


Figure 6.1: The block diagram of ring topology based PON using OADM

The internal structure of transmitter array is shown in figure 6.2. It consists of four Continuous Wave (CW) laser sources with 100 GHz channel spacing. These signals are multiplexed using 4x1 Multiplexer with 50 dB extinction ratio. To boost up signals, Semiconductor Optical Amplifier (SOA) with 5 dB gain is used before transmitting the signals to OADM.

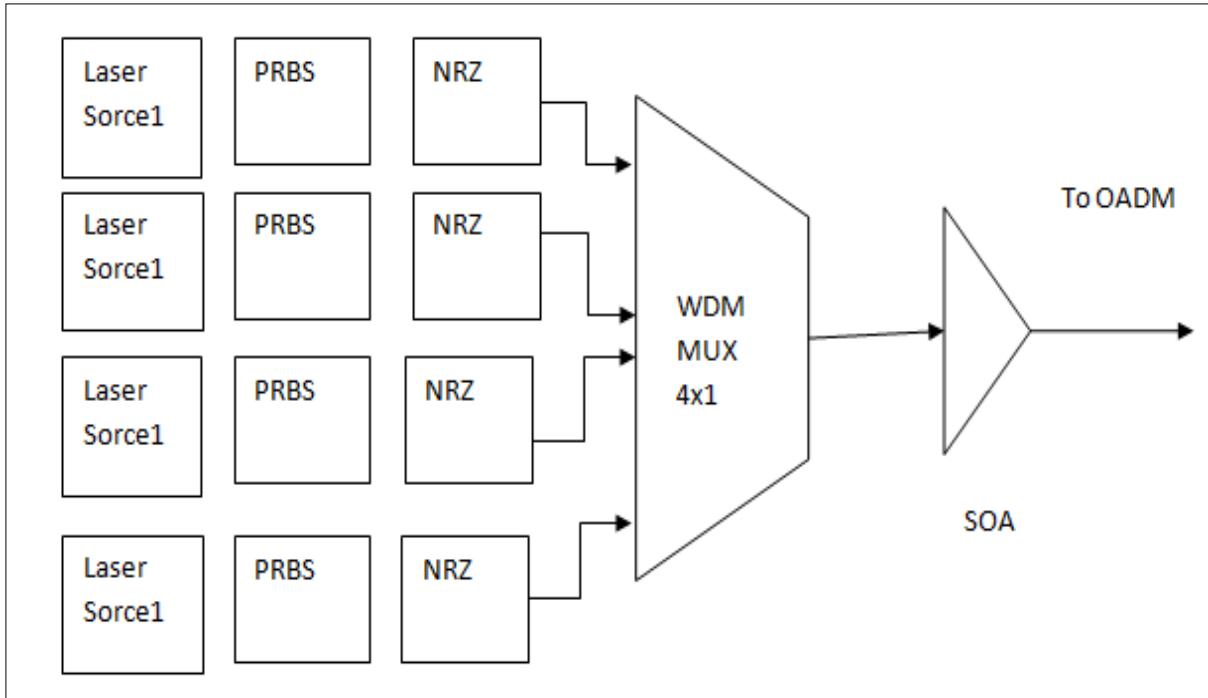


Figure 6.2: Internal structure of transmitter array

The internal structure of receiver array is shown in figure 6.3. The data is de-multiplexed using 1x4 WDM De-multiplexer. The signals are detected by PIN photo detectors as shown in figure. Various signal analyzers are used to observe the results.

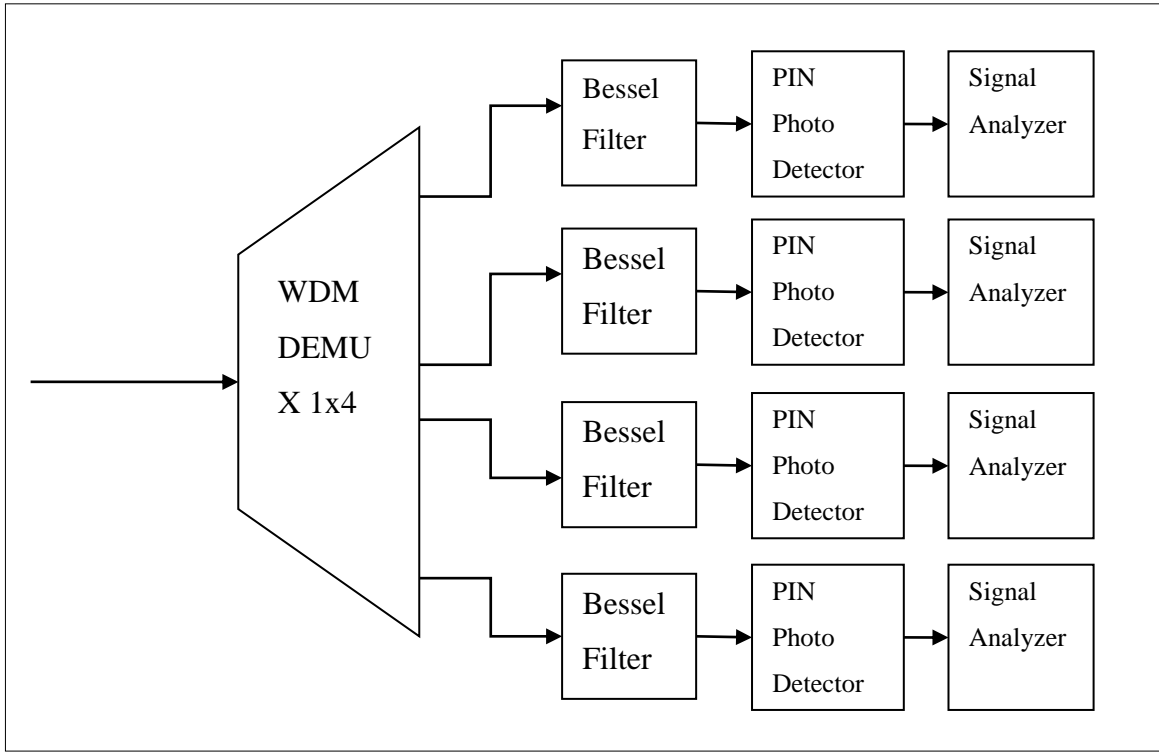


Figure 6.3: The internal structure of receiver array

6.1.2 Result and Discussion

The performance of the ring based PON architecture is observed at each node by varying the channel spacing and input power. The graph for Q factor versus number of users at each node for various channel spacing is shown in figure 6.4.

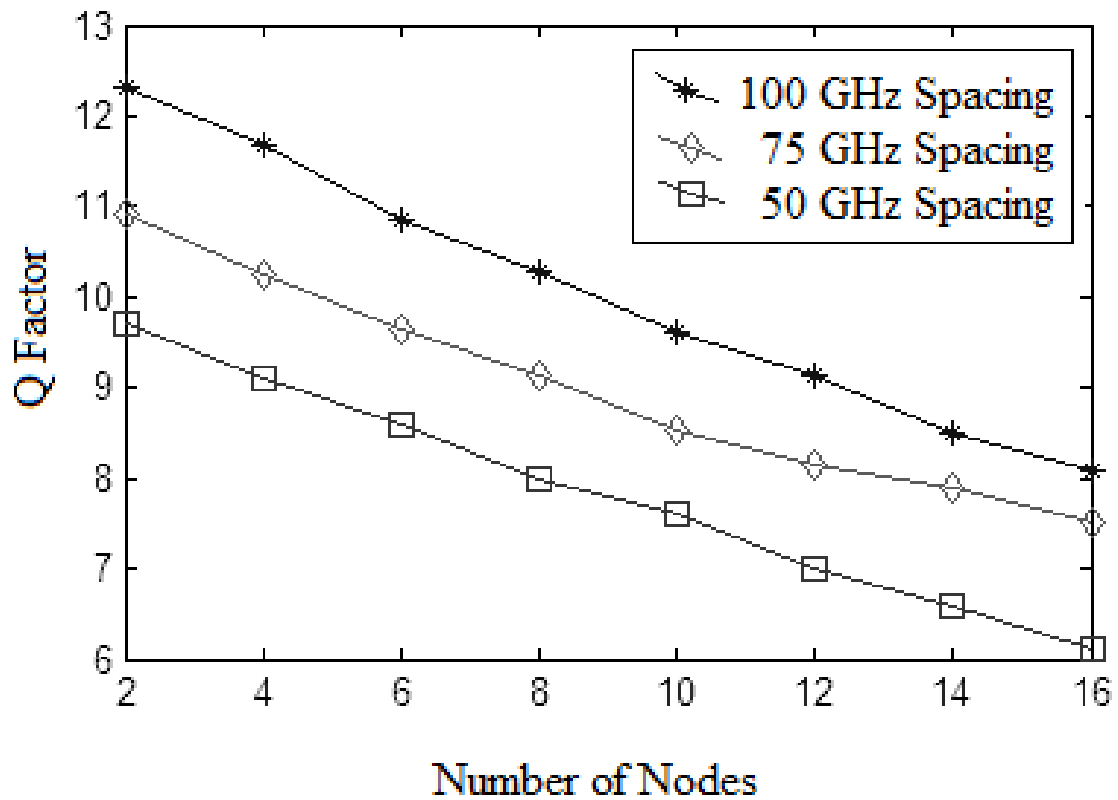


Figure 6.4: Q factor versus number of nodes for various channel spacing at 10 Gbps data rate

It is evident that the Q factors of 12.3 & 8.1 for 100 GHz spacing, 10.92 & 7.5 for 70 GHz spacing and 9.7 & 6.1 for 50 GHz spacing are achieved at 1st and 16th node respectively. The graph for Q factor versus number of nodes for various input powers at 10 Gbps data rate is shown in figure 6.5.

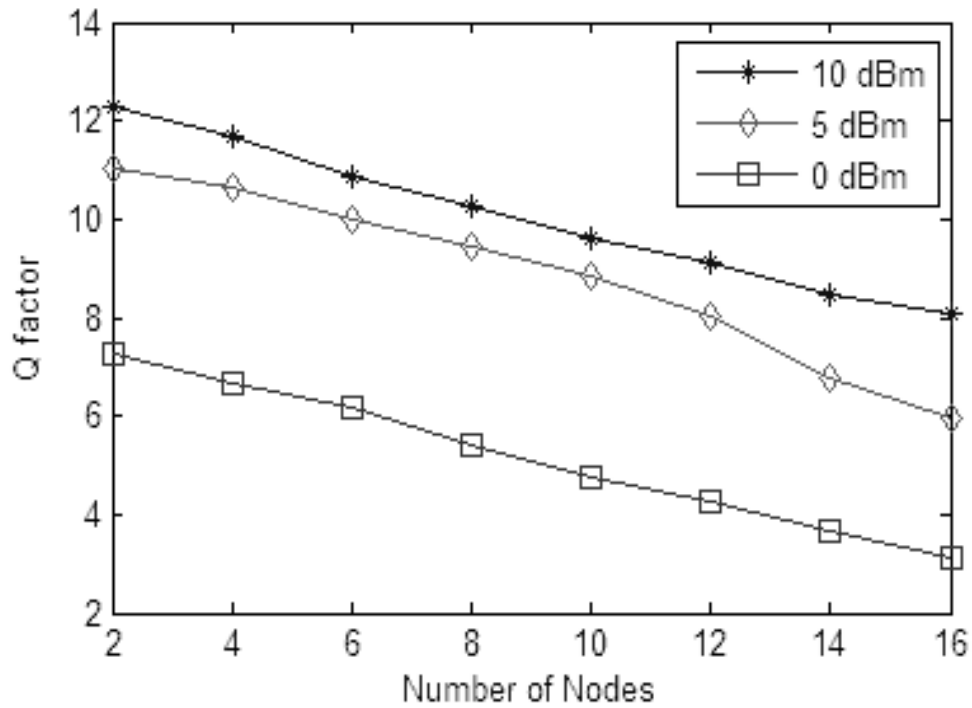


Figure 6.5: Q factor versus number of nodes for various input powers at 10 Gbps data rate. It is evident that the Q factors of 12.3 & 8.1 for 10 dBm input power, 11.03 & 5.93 for 5 dBm input power and 7.24 & 3.1 for 0 dBm input power are achieved at 1st and 16th node respectively. The graph for Q factor versus number of nodes for different data rates is shown in figure 6.6.

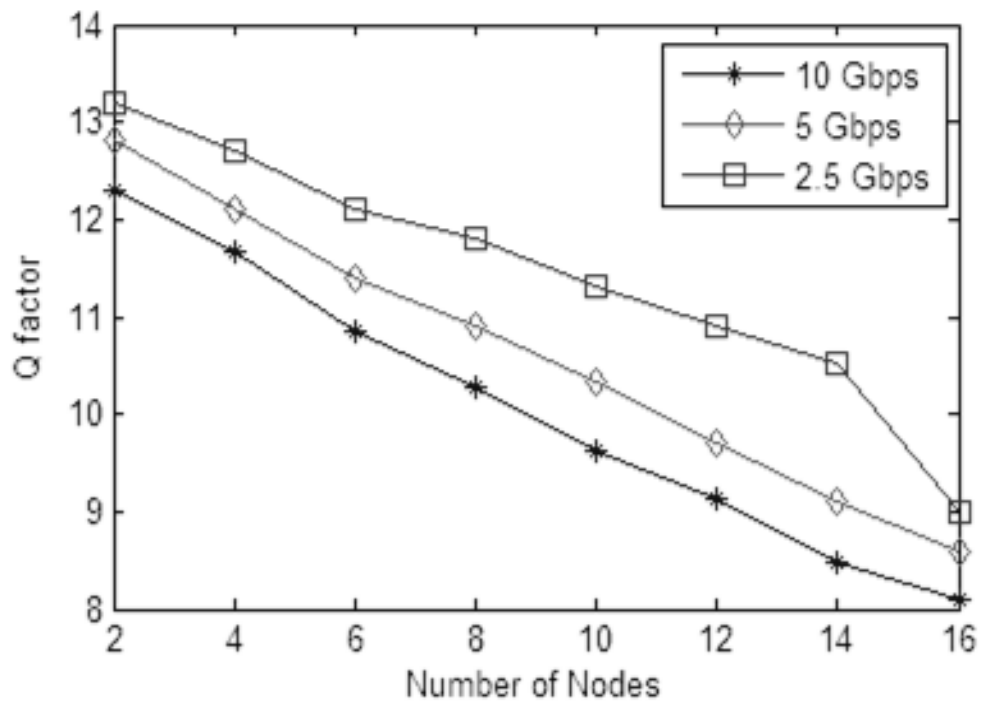


Figure 6.6: Q factor versus number of nodes for different data rates

It is evident that the Q factors of 12.3 & 8.1 for 10 Gbps data rate, 12.8 & 8.6 for 5 Gbps data rate and 13.2 & 9 for 2.5 Gbps data rate are achieved at 1st and 16th node at 100 GHz channel spacing and 10 dBm input power respectively.

6.2 PON using Hybrid Topology Network

The tendency to make intensive use of meshed and reconfigurable networks impose new stringent requirements on the designing of different topologies for modern networks to sufficiently reduce inter-channel crosstalk. As far as, the degradation in signal quality or in amplitude level is present due to various losses, different topologies are important to use at optimal position. Benyang Chen et al. [84] proposed ring topology based WDM PON using a feeder fiber and investigated for insertion losses due to AWG, coupler, splitter, fiber and optical switch. As per the literature survey, the ring architecture is proposed for the WDM/ TDM PON systems, but architectures based on combination of various topologies have been rarely defined. We have extended the previous ring network in terms of number of users to 1024 with hybrid (ring-tree) topology.

6.2.1 System Setup

The block diagram of PON system based on hybrid (ring-tree) using OADM is shown in figure 6.7. The ring network is improved in terms of number of users to 1024 with hybrid (ring-tree) topology form using sixteen Optical Add Drop Multiplexers (OADMs) and one hundred forty four star hubs (1x8). Four channels at 193.1 THz center frequency with 100 GHz channel spacing can be added and dropped at each OADM. The OLT consists of four Continuous Wave (CW) laser sources. These signals are multiplexed using 4x1 Multiplexer with 50 dB extinction ratio. To boost up the signals, SOA with 5 dB gain is used before transmitting the signals to OADM. 10 Gbps data is successfully transmitted up to 1500 Km transmission distance.

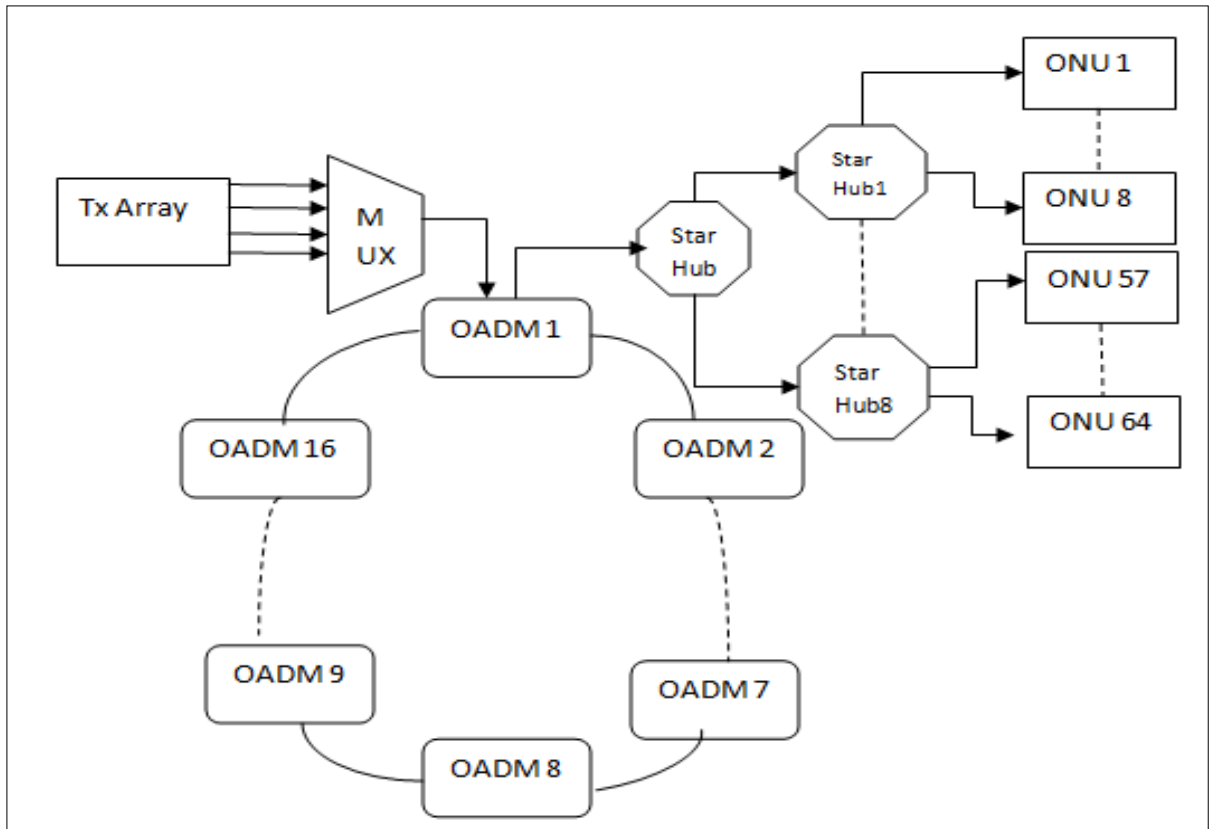


Figure 6.7: The block diagram of PON based on hybrid (ring-tree) topology using OADM

6.2.2 Result and Discussion

BER versus number of users with different data rates is shown in figure 6.8. BER is observed for the system by simulating at 100 GHz channel spacing for all line rates.

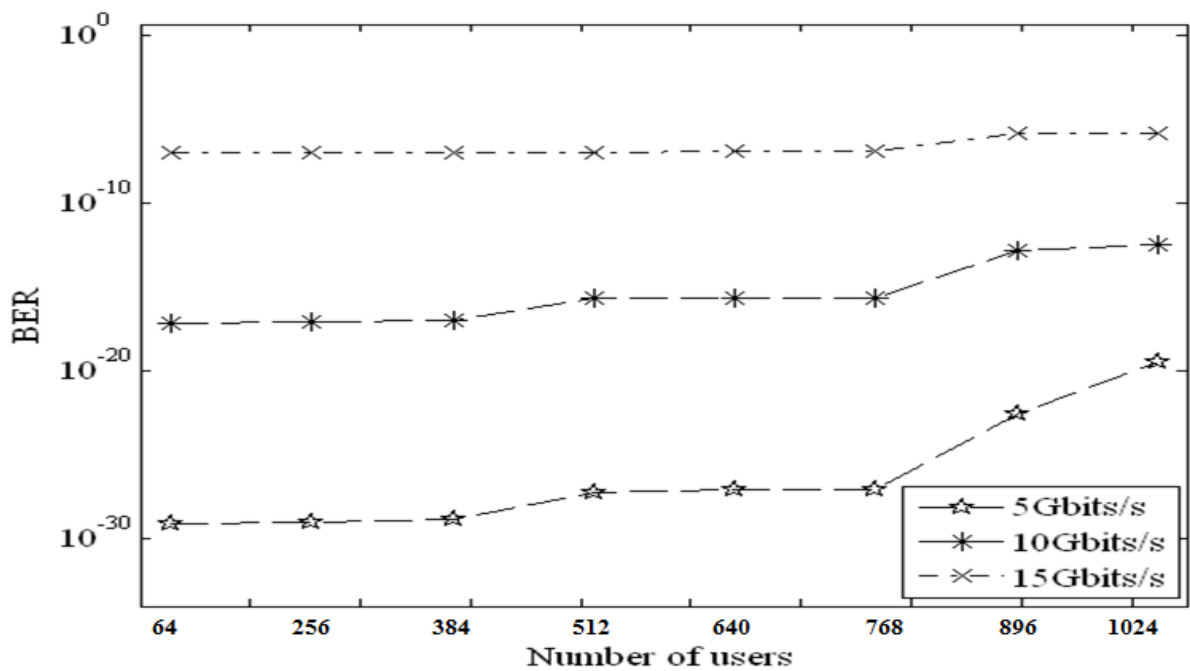


Figure 6.8: BER versus number of users with different data rates

BER of (7.3×10^{-29} to 5.1×10^{-22}) with 5 Gbps, (from 3.2×10^{-17} to 3.1×10^{-14}) with 10 Gbps and (from 5.8×10^{-9} to 1.7×10^{-7}) with 15 Gbps is achieved for 64 to 1024 number of users respectively. It is also shown that BER increases with the increase in number of users. Q factor versus number of users for PON system using hybrid topology is shown in figure 6.9.

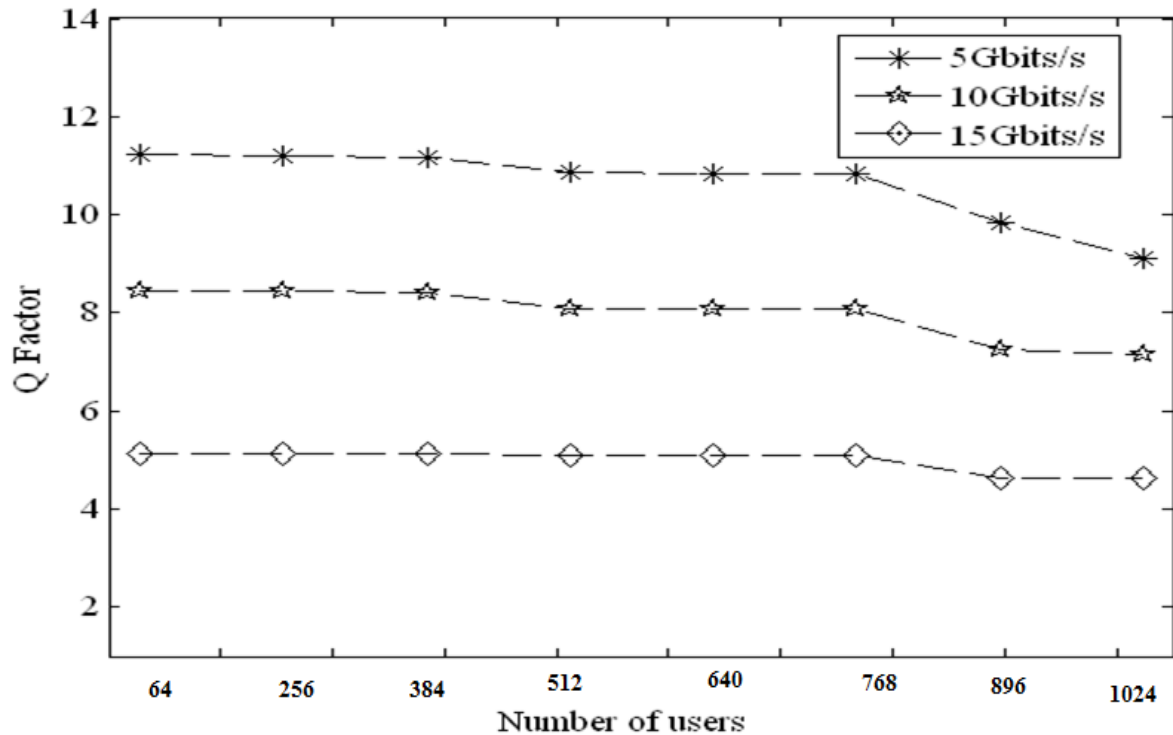


Figure 6.9: Q factor versus number of users with different data rates

It is evident that Q factor of (11.63 to 9.72) with 5 Gbps, (from 8.3 to 7.82) with 10 Gbps and (from 5.29 to 4.96) with 15 Gbps is achieved for 64 to 1024 number of users respectively. It is also shown that Q factor decreases with the increase in number of users.

6.3 PON with Path Protection Topology

In high capacity multi-terabit optical communication system, the choice of network configuration and protection of the data in case of failure are the main key factors in designing of next generation networks. Also, the combination of different topologies is the hot research area to enhance system capacity with improved performance. Yejun Liu et al. [77] proposed PON system with protection scheme based on single Shared-Risk Link Group (SRLG) failure. The two algorithms based on Backup Fibers Protection (BFP) have been proposed to make the network reliable in case of any connection failure occurs. The data is sent through backup fibers with optimum delay in failure. Chuan-

Ching Sue et al. [80] proposed a WDM PON with full protection scheme using feeder and distribution fibers. After the comparison of different proposed scheme with existing PON standards from the literature, it is concluded that most of the schemes are based on extra fiber (stand by or back up fiber) for providing protection. In this section, we proposed a fault protection scheme for hybrid passive optical network using ring topology.

6.3.1 System Setup

The block diagram of PON system with path protection topology is shown in figure 6.10.

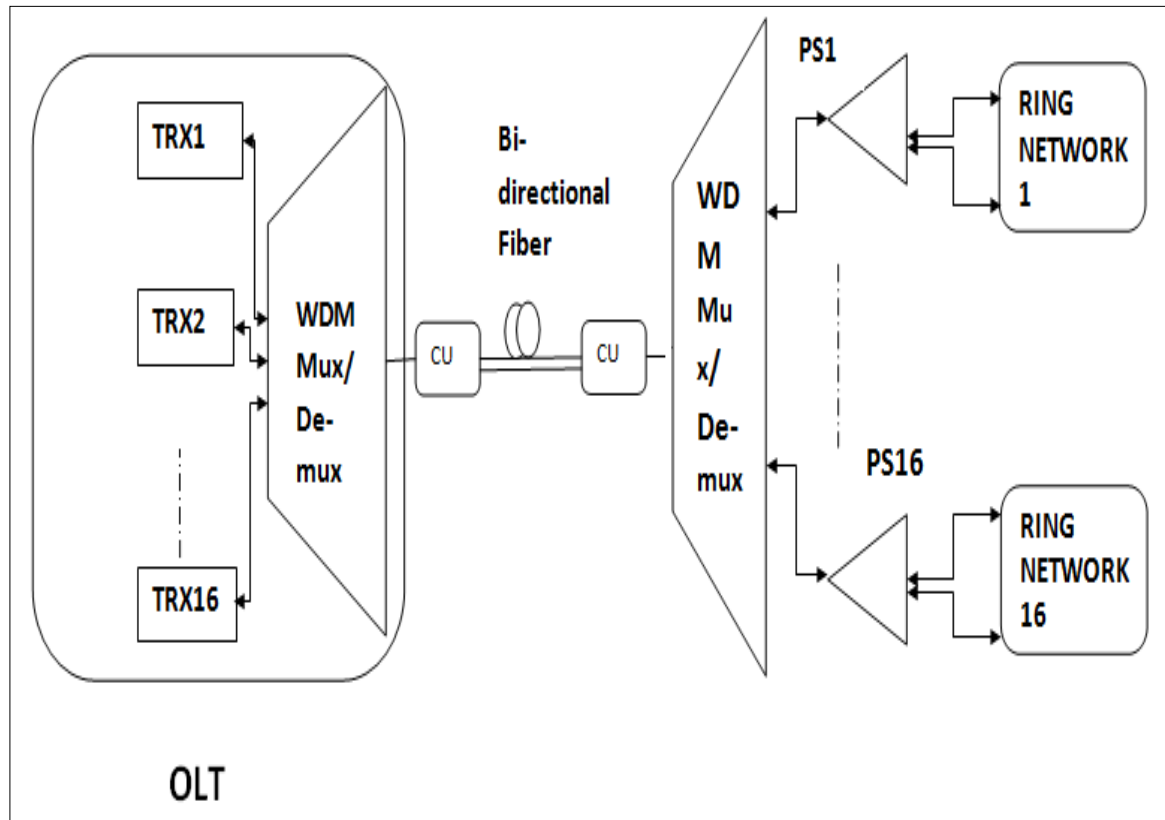


Figure 6.10: The block diagram of PON system with path protection topology

The OLT is equipped with sixteen photonic integrated circuits based TRX arrays (TRX1 to TRX16) along with a bidirectional optical fiber of 100 Km link. The data is demultiplexed into 16 wavelengths of upstream and downstream. It is further split to 128 ONUs using sixteen 1x8 power splitters and combiners with 10 ps time delay. The configuration of ring network for path protection topology is shown in figure 6.11. In this network, first four nodes of the ring are connected clockwise direction and the remaining four nodes are connected anti-clockwise direction. A control circuitry is also installed between each node. The fourth and fifth nodes are simply connected but there is no flow of data between them in general conditions i.e. if there is no fault or breakage in the

system. If any fault or breakage occurs in the fiber between first four clockwise connected nodes, then the control circuitry detects the breakage and connects the node to anti clockwise adjacent node.

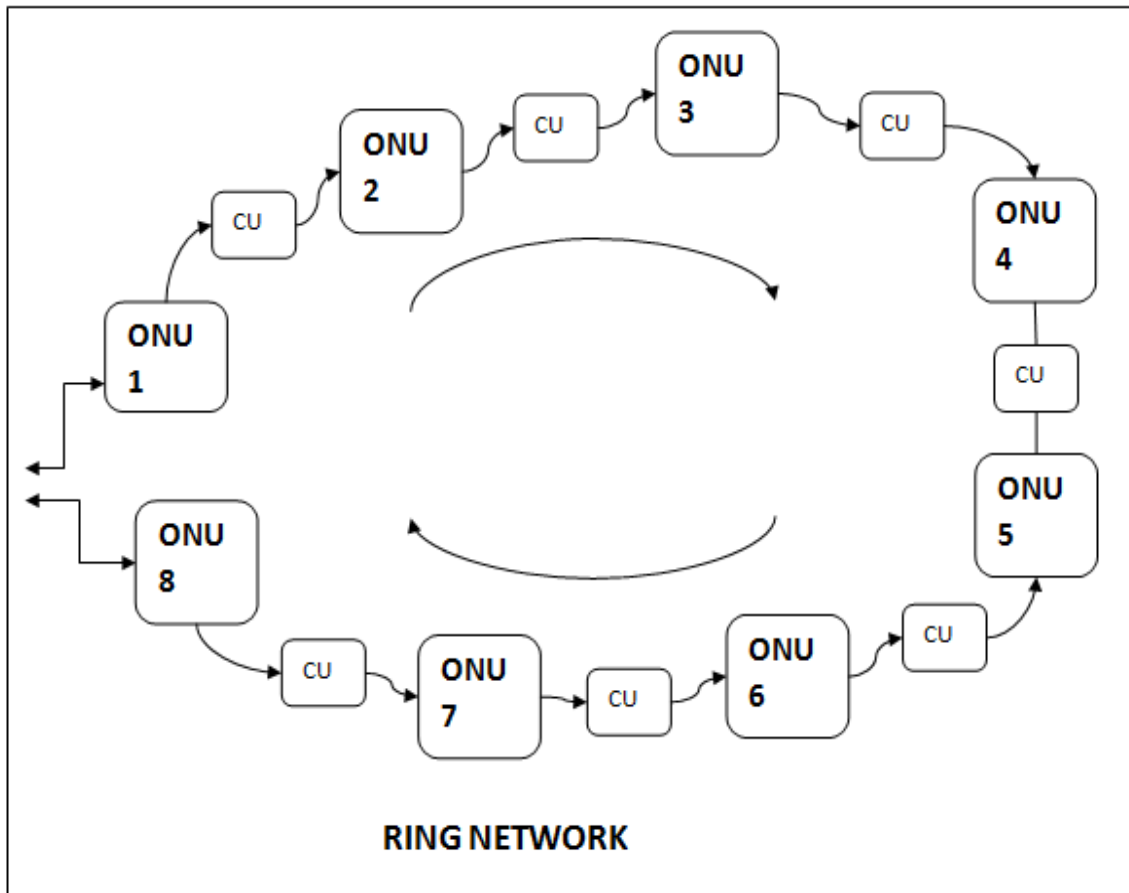


Figure 6.11: The configuration of ring network for path protection topology

The node before the breakage will remain connected to clockwise adjacent node. For example, if a fault occurs between second and third nodes, then the first two nodes will communicate clockwise and third node will connect to fourth node anticlockwise through connecting fourth and fifth nodes anti clockwise. Similarly, if the fault occurs between anti clockwise nodes, then the node after the fault will automatically connected with clockwise adjacent node and the node before the fault will remain connected with clockwise adjacent node. If the fault occurs between fourth and fifth nodes then the system will work in the same manner. So, this scheme provides the full fault protection to passive optical network system without installing the extra fiber [85].

6.3.2 Result and Discussion

The BER versus distance for various data rates i.e. 5, 10 and 15 Gbps at 8th ONU is shown in figure 6.12.

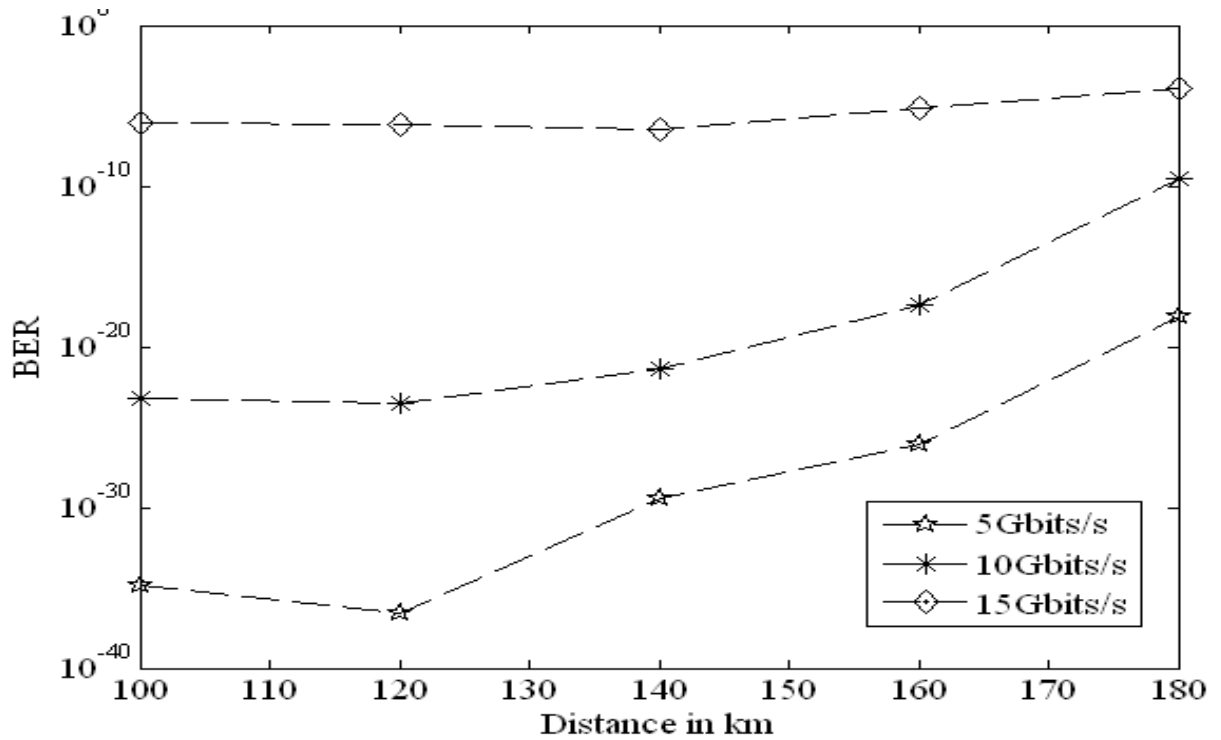


Figure 6.12: BER versus distance for various data rates at 8th ONU

BER of (1.4×10^{-34} to 3.6×10^{-19}) with 5 Gbps, (from 5.1×10^{-23} to 6.7×10^{-13}) with 10 Gbps and (from 3.6×10^{-8} to 2.4×10^{-6}) with 15 Gbps is achieved at 100 to 180 Km distance respectively. It is also shown that BER increases with the increase in the distance. The Q factor versus distance for various data rates i.e. 5, 10 and 15 Gbps at 8th ONU is shown in figure 6.13.

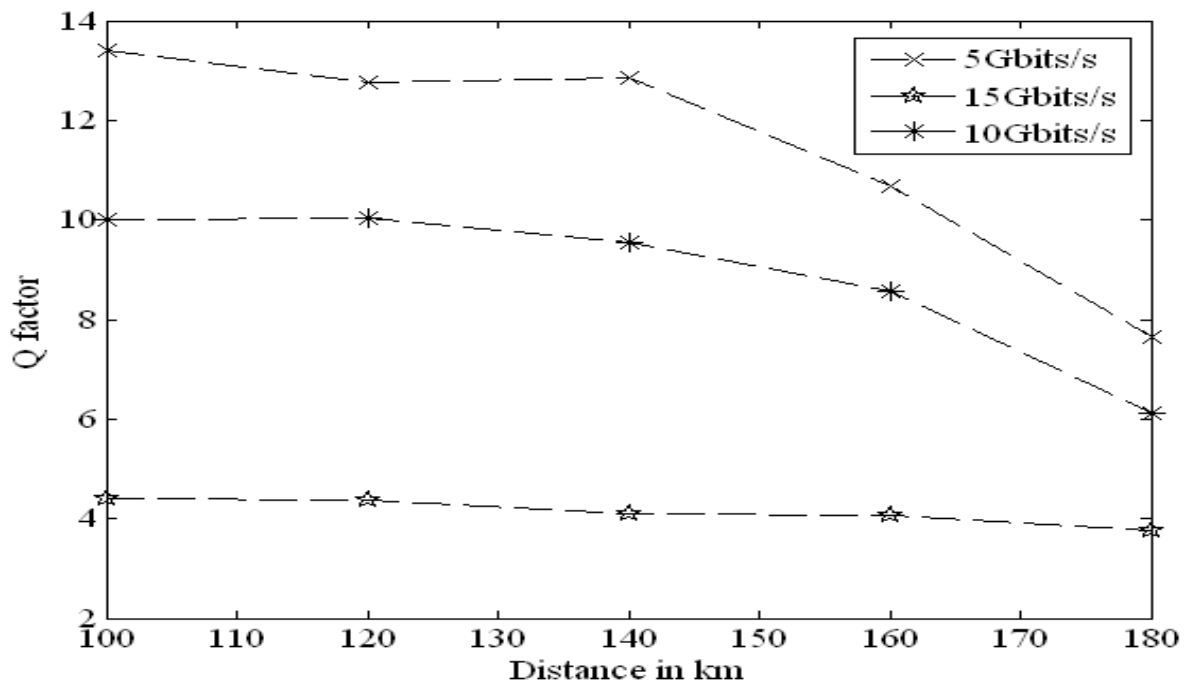


Figure 6.13: Q factor versus distance for various data rates at 8th ONU

It is evident from the figure that Q factor varies (from 13.23 to 7.93) with 5 Gbps, (from 10.3 to 6.16) with 10 Gbps and (from 4.49 to 3.86) with 15 Gbps is achieved at 100 to 180 Km distance respectively. It is also shown that Q factor decreases with the increase in the distance. BER versus distance for various data rates i.e. 5, 10 and 15 Gbps at 128th ONU is shown in figure 6.14.

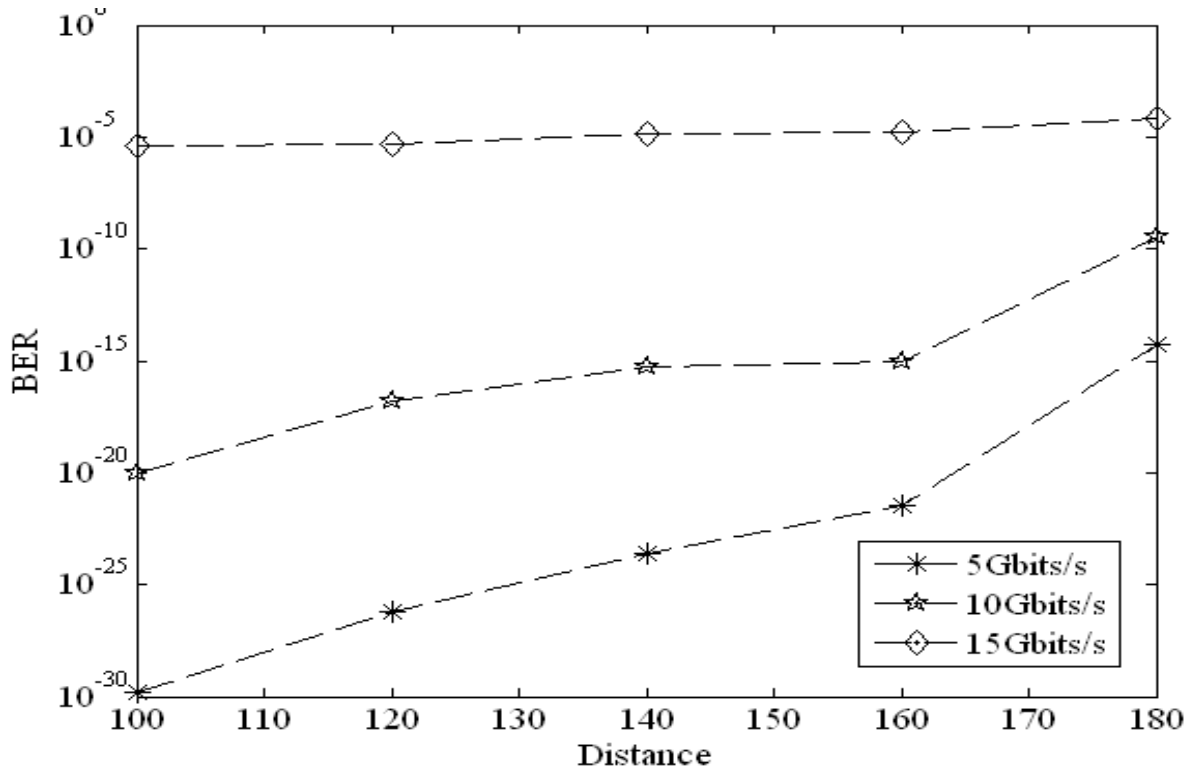


Figure 6.14: BER versus distance for various data rates at 128th ONU

BER of (4.3×10^{-29} to 1.1×10^{-17}) with 5 Gbps, (from 2.2×10^{-20} to 8.1×10^{-12}) with 10 Gbps and (from 8.6×10^{-6} to 4.3×10^{-4}) with 15 Gbps is achieved at 100 to 180 Km distance respectively. It is also shown that BER increases with the increase in the distance. The Q factor versus distance for various data rates i.e. 5, 10 and 15 Gbps at 128th ONU is shown in figure 6.15. It is evident from the figure that Q factor varies (from 11.41 to 8.83) with 5 Gbps, (from 10.1 to 7.21) with 10 Gbps and (from 4.86 to 3.75) with 15 Gbps is achieved at 100 to 180 Km distance respectively. It is also shown that Q factor decreases with the increase in the distance.

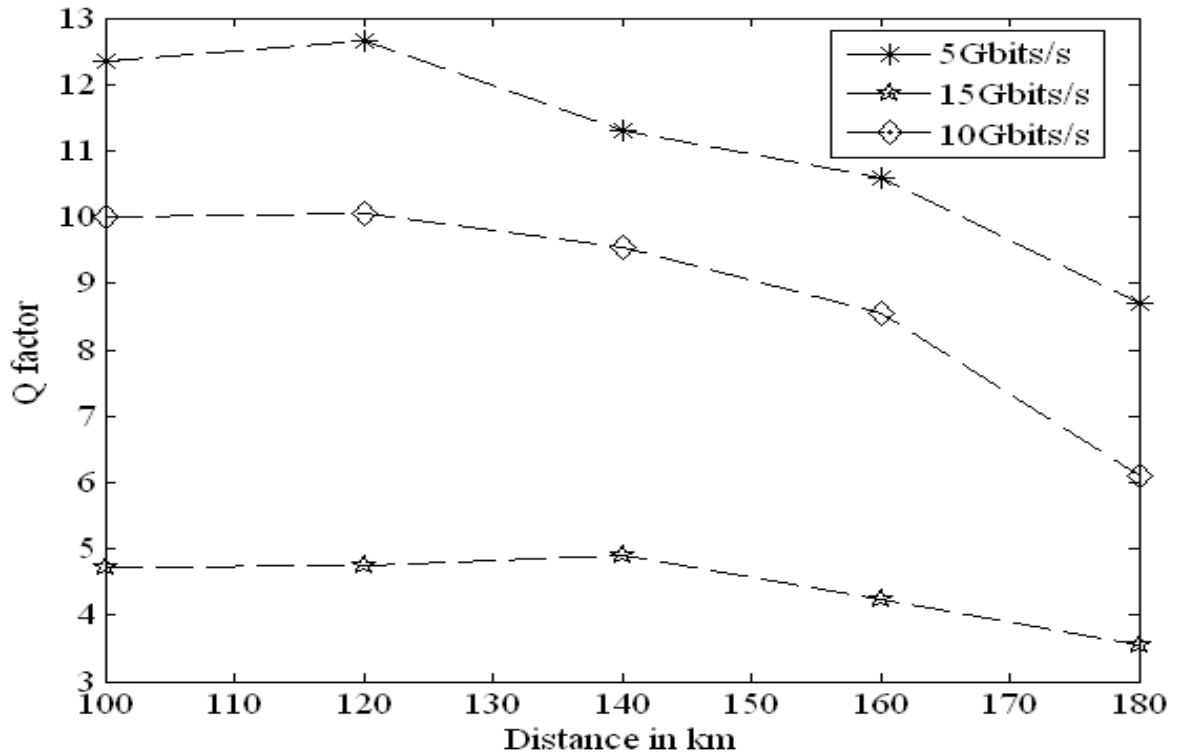


Figure 6.15: Q factor versus distance for various data rates at 128th ONU

6.4 Conclusion

A network for 1024 number of users with ring-tree topology form using sixteen Optical Add Drop Multiplexers (OADMs) and one hundred forty four star hubs (1x8) has been proposed. Four channels at 193.1 THz center frequency with 100 GHz channel spacing can be added and dropped at each OADM. Input signals with 10 Gbps data have been successfully transmitted up to 1500 Km transmission distance. A fault protection scheme for ring based passive optical network has also been proposed. All the nodes were connected in two directions i.e. clockwise and anti clockwise with control circuit. The respective nodes were connected in opposite direction by the control circuit in case of fault. In this way, full fault protection has been provided by the proposed scheme without the requirement of extra standby fiber.

Chapter 7

Conclusion, Recommendations and Future Scope

7.1 Conclusion

The PON (Passive Optical Network) architecture provides a common platform towards achieving a cost effective optical access network. This thesis presents the performance analysis of hybrid Wavelength Division Multiplex/ Time Division Multiplex (WDM/TDM) PON system. The motivation and objective of this thesis is to perform an in-depth analysis of the various problems (such as designing of various architectures, optimum selection of amplifier, analysis and mitigation of various fiber nonlinearities and designing of networks with different topologies) for increasing the capacity, transmission distance and flexibility. Various hybrid PON architectures have been proposed and the outcomes presented have been validated using extensive simulations. The major outcomes obtained from this study are summarized as follows:

1. Various architectures of hybrid PON have been proposed and evaluated. Triple play services (video, voice and data) have been accessed by 128 Optical Network Units (ONUs). It has been found that NRZ data format and QAM modulation schemes give better performance. Further, a bidirectional Hybrid PON for different data rates i.e. 1.25, 2.5, 5 and 10 Gbps has also been presented. To realize bidirectional transmission in single fiber, a circulator has been used to isolate the uplink signals from downlink signals. In the next architecture, a network using Common Carrier to All ONUs (CCAONUs) technique has been proposed. In this technique, a carrier for upstream has been generated at the central office with downstream carrier and remodulated for upstream transmission at the subscriber end making ONU very simple and cost effective. So, there was no requirement of the laser source to generate the optical carrier at the ONU end. In this way, with this extra laser source at central office, the system has been made cost effective by decreasing the number of laser sources equal to the number of ONUs.
2. Further, different aggressive schemes to reduce the energy consumption viz. No Buffer (NB), With Buffer (WB), Reduced Buffer (RB) and Reduced Buffer with Small Packet (RBSP) have been proposed. The performance of these schemes for downstream and upstream data by exploring the relationship between power

consumption and average traffic load has been evaluated. RBSP scheme has been found most efficient scheme with consumption of 2 to 6.2 mW and 3.5 to 7.5 mW power with 0.1 to 0.8 traffic load for upstream and downstream respectively.

3. A bidirectional Hybrid PON for Raman, Semiconductor Optical Amplifier (SOA) and Erbium Doped Fiber Amplifiers (EDFA) using polarization modulation technique with QAM at 5 Gbps data rate has been investigated. It has been shown that the data with 5 Gbps rate can be transmitted and received by 120, 90 & 40 ONUs up to 70 Km and 110, 60 & 35 ONUs up to 80 Km transmission distance with EDFA, SOA and Raman amplifiers respectively. The system has also been enhanced to 10 Gbps data rate with 128 ONUs. The system performance has been improved using polarization modulation with 16-QAM to utilize the maximum bandwidth. It has been observed that EDFA amplifier shows better performance than SOA and Raman.
4. The system has been analyzed theoretically for the various fiber nonlinearities like Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), Four Wave Mixing (FWM) and Cross Phase Modulation (XPM). Different wavelengths for downstream and upstream i.e. 1550 nm and 1300 nm have been used to minimize the crosstalk effect of same wavelength in the fiber respectively. The proposed system was very simple, flexible, expandable and cost effective. The system performance in terms of CNR (carrier to noise ratio) and output power has also been analyzed. Various results in 2D and 3D have been presented to analyze the impact of these nonlinearities with CNR, input power, received output power, BER and number of ONUs. It has been observed that due to these fiber nonlinearities, the system performance was affected in terms of desired launched power, expansion of the network, number of ONUs etc. It has also been found that 10 Gbps data can be transmitted and received up to 190 and 185 Km distance with 256 ONUs with minimum acceptable Q factor without any inline amplification respectively. The impact of non linearity like RS and SBS has also been mitigated in the proposed network.
5. Further, PON systems for Mixed Line Rates (MLRs) i.e. 10/ 20/ 40 Gbps to reduce the crosstalk have been proposed. The investigation has been focused on uniform channel spacing and mixed channel spacing for MLRs. It has been found

that mixed channel spacing gives better performance than uniform channel spacing.

6. A network for 1024 number of users with ring-tree topology form using sixteen Optical Add Drop Multiplexers (OADMs) and one hundred forty four star hubs (1x8) has been proposed. Four channels at 193.1 THz center frequency with 100 GHz channel spacing have been added and dropped at each OADM. The input signal with 10 Gbps data rate has been successfully transmitted up to 1500 Km transmission distance.
7. A cost effective fault protection scheme has also been proposed for hybrid passive optical network using ring topology. In this network, first four nodes of the ring have been connected clockwise direction and the remaining four nodes are connected anti-clockwise direction. A control circuitry has also been installed between each node. A full fault protection to PON system has been provided by the proposed scheme without installing the extra standby fiber.

7.2 Recommendations

The recommendations on the basis of results obtained in previous chapters are given below:

1. The proposed architectures are recommended to increase the hybrid PON system ability against large number of ONUs at longer distance. The system can also be used for the networks where different service classes (audio, video and data) for multimedia traffic can be served accordingly.
2. By using extra carrier at the central office, number of laser sources can be eliminated by CCAONU technique. So, this technique has been proven to be very cost effective and can be used to reduce the overall cost of the network.
3. The energy saving is the main issue in today's networks. Reduce buffer with small packet scheme consumes very less power for operation with small delay in packet transfer. So, this scheme can be used for green energy saving networks.
4. Various fiber nonlinearities degrade the overall performance of the system. The heterogeneities in the data rates and channel spacing are also a prominent solution to mitigate the crosstalk effect.
5. The protection scheme using single fiber can be used to make the network reliable at very low cost.

6. The Ring Tree topology has been proven a good solution to increase the number of users.

7.3 Future Scope

1. With the advancement in technology, there is continuous need in the optical networks to operate at higher bit rates. In future, hybrid PON can be extended to large number of ONUs in long-haul systems for high bit rates of greater than 40 Gbit/s per channel or more.
2. Since channel spacing is also a major concern. The hybrid PON can be enhanced using lesser channel spacing.
3. The mixer of different amplifiers should be explored for covering much wider gain bandwidth product. The network can also be upgraded to wireless networks at the user's end.
4. The performance of the system can be enhanced by mitigation of power transients using dynamic EDFA component with the surviving channels.
5. The energy conservation will be a dominant area of research for next generation networks.
6. The heterogeneities in the data rates and channel spacing can be explored to mitigate the crosstalk effect. The protection scheme using single fiber can become a prominent solution to make the network reliable at very low cost.
7. The CCAONU technique also plays an important role to reduce the cost of the network. Various algorithms to minimise the effect of overall crosstalk can also be considered in the future.

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