DESIGN, DEVELOP AND PERFORMANCE ANALYSIS OF A GIGABIT PASSIVE OPTICAL NETWORK FOR QUAD PLAY ARCHITECTURE

by

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MASTER OF SCIENCE

IN

INFORMATION AND COMMUNICATION TECHNOLOGY

Institute of Information and Communication Technology

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

August, 2017

The thesis titled **"DESIGN, DEVELOP AND PERFORMANCE ANALYSIS OF A GIGABIT PASSIVE OPTICAL NETWORK FOR QUAD PLAY ARCHITECTURE"** submitted by Md. Hayder Ali, Roll no: 0411312003P, session April 2011 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Information and Communication Technology on 9 August, 2017.

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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DEDICATION

THIS THESIS IS DEDICATED

TO

MY PARENTS

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List of Abbreviations

GPON	Gigabit Passive Optical Network
FTTx	Fiber to the x
FTTN	Fiber to the Node or Neighbourhood
FTTC	Fiber to the Curb or Cabinet
FTTP	Fiber to the Premises
FTTB	Fiber to the Building or Basement
FTTH	Fiber to the Home
PON	Passive Optical Network
LDP	Local Distribution Point
BDB	Building Distribution Box
MPLS	Multi-Protocol Level Switching
OLT	Optical Line Terminal
ONU	Optical Network Unit
ONT	Optical Network Terminal
BPON	Broadband Passive Optical Network
GEPON	Gigabit Ethernet Passive Optical Network
EPON	Ethernet Passive Optical Network
ODF	Optical Distribution Frame
IPTV	IP Television
VoD	Video on Demand
HDTV	High-Definition Television
TDM	Time-Division Multiplexing
WDM	Wavelength-Division Multiplexing
SLA	Service Level Agreement
OCS	Optical Circuit Switching
OCS	Optical Cross Connect
OBS	Optical Burst Switching

ITU	International Telecommunication Union
TDMA	Time Division Multiple Access
CO	central office
EP2P	Ethernet Point to Point
TP	Triple Play
QP	Quad Play

List of Symbols

Λ	Period of grating
β	Propagation constant of the mode in the core
h	Planck's constant
f_c	Carrier frequency
M	Average number of photons received during a 1 bit
k_B	Boltzmann's constant
B_e	Electrical bandwidth of the receiver
$\sigma^2_{thermal}$	Thermal noise of optical receiver
B_0	Optical bandwidth of receiver
T	Room temperature in degree kelvin
σ^2_{shot}	Shot noise of optical receiver
R_L	Load resistor of photodetector
I_1	Photo current during binary '1' bit
I_0	Photo current during binary '0' bit
σ^2_1	Variance of output of the receiver for binary '1'
σ^2_0	Variance of output of the receiver for binary '0'
η	Quantum efficiency
P_r	Received power

λ	Wavelength
R	Reflectivity of grating
σ^2_{RIN}	Relative intensity noise
Ω	Coupling coefficient
Δn	Amplitude of the induced refractive-index perturbation

Acknowledgements

First of all, I would like to thank Almighty Allah for Allah's mercy and charity. This thesis is the most significant accomplishment in my life and would have been impossible without the will and wish of the Almighty and I am grateful to Allah.

Most of all, I would like to express my deepest gratitude to my supervisor, Dr. Md. Saiful Islam, Professor and Director, Institute of Information and Communication Technology (IICT), Bangladesh University of Engineering and Technology (BUET), for introducing me in the arena of optical communication and for his continuous inspiration, guidance and invaluable support during this research work.

I would like to thank the members of my thesis examination committee for their precious time in understanding my work and their insightful comments. I would like to express my thanks to Dr. Md. Rubaiyat Hossain Mondal, Associate Professor, IICT, BUET and Dr. Hossen Asiful Mustafa, Assistant Professor, IICT, BUET for their valuable advices. I also express my thanks to Dr. M. Mofazzal Hossain, Professor and Chairman, Department of Electronics and Communications Engineering, East West University (EWU) for his valuable comments.

Next, I would like to thank all the teachers and staffs of IICT, BUET for their cordial help and assistance during my study period.

Finally, I would like to thank my family for their continuous support, encouragement and sacrifice throughout the years and I will be obliged to them forever for all they have done.

Abstract

Accessing Internet is going to be a fundamental right like other basic human rights. No matter how often a user uses Internet, waiting for a web page to load is really an annoyance. To overcome this situation, Internet speed has increased significantly in the past decade to keep pace with the demand of users, new services and bandwidth-hungry applications. These demands include as multimedia content based e-commerce, video on demand, high definition TV, IPTV, online gaming, social media, etc. Lots of different technologies like gigabit Ethernet, mobile Internet, etc, that have been trying to cater and satisfy the user demand. Gigabit passive optical networks (GPON) is one of the high-speed access technology which offers triple play service (i. e., data, voice and video) GPON is easier, faster and low cost. GPON can transport Ethernet, ATM and TDM (PSTN, ISDN, E1 and E3) traffic. It has been widely accepted by Internet service providers and operators in terms of bandwidth upgrade, service bearer as well as passive network maintenance. High bandwidth capacity, high quality and multi-play services through a single channel presents a strong business opportunity for telecom operators as it provides support which includes voice, Ethernet, ATM, leased lines and others. GPON offers simple operation, administration, maintenance and provisioning capabilities as well as end-to-end service management. It not only provides substantially higher efficiency as a transport network, but also delivers simplicity and superb scalability for future expansion in supporting additional services.

Convergence of multiple technologies and services are the requirements of today's Internet savvy users. GPON provides service using a wide spectrum of wavelength range from 1310 nm to 1610 nm. SDH traffic with GPON triple play, that is GPON quad, is very much necessary to meet customer demands. GPON quad play is not available now. In this research work, quad play (i. e., voice, video, data and SDH traffic) architecture is proposed. In this scheme, a wavelength multiplexer is used instead of Erbium doped fiber amplifier combiner with a fixed wavelength, which increases the performance substantially. It is found that using 1550 nm wavelength, the proposed design provides multiple services with high performance to the end user.

Chapter 1

Introduction

1.1 Introduction

Previously, the most used access network technologies are ADSL and ADSL2+ over copper wire. With the arrival of new multimedia applications like voice IP (VoIP), video on demand (VoD) or IP television (IPTV), more capacity and QoS are needed. New Fiber to the Home(FTTH) technologies replace link copper by optical fiber. FTTx is a generic term for any broadband network architecture using optical fiber to replace all or part of the usual metal local loop used for last-mile telecommunications. Fiber to the x (FTTx) is a collective term for various optical fiber delivery topologies that are categorized according to where the fiber terminates. Fiber access is one of the most important technologies in the next generation network. It increases the access layer bandwidth and builds a sustainable-development access layer network. Optical Access Network(OAN) adopts technologies: active point-to-point (P-P) Ethernet and passive optical network (PON). There are many common subsets of FTTx like-fiber to the node or fiber to the neighbourhood (FTTN) , fiber to the curb or fiber to the cabinet (FTTC), fiber to the premises (FTTP), fiber to the building or fiber to the basement (FTTB), fiber to the home (FTTH) etc.

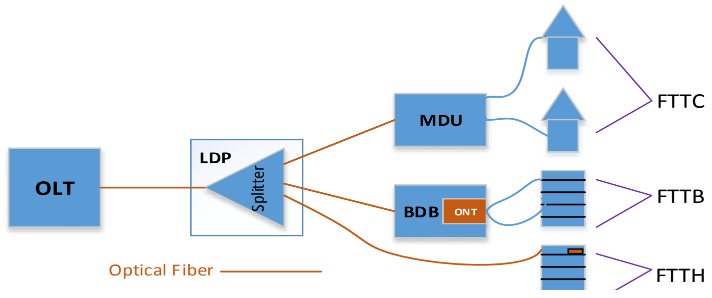


Figure-1.1: Open Access Network Structure (FTTx)

Figure-1.1 shows that if splitted fiber directly goes to client Premises/ Home, then client will enjoy the device dedicatedly and if splitted fiber goes to building's basement, then from Optical Network Unit(ONU)/ Optical Network Terminal(ONT) client will enjoy their connectivity by short UTP cable.

1.2 Optical Communication System

Communication means the exchange of information which may be voice, video, or data. So, a communication system transmits information from one place to another place. Communication systems exchange signals between two or more entities in a form suitable to process and manipulate most economically. The basic principle of a communication system is to bridge two entities at different locations.

Twenty first century is the era of information technology (IT). There is no doubt that IT has achieved an exponential growth through the modern telecommunication systems. Particularly, optical fiber communication plays a vital role in the development of high quality and high-speed telecommunication systems. Today, optical fibers are not only used in telecommunication links but also used in the Internet and local area networks (LAN) to achieve high signaling rates.

1.3 Evaluation of Optical Communication

Even though an optical communication system had been conceived in the late 18th century by a French Engineer Claude Chappe who constructed an optical telegraph, electrical communication systems remained the dominant means of communication. In 1966, Kao and Hockham proposed the use of optical fiber as a guiding medium for the optical signal [8]. Four years later, a major breakthrough occurred when the fiber loss was reduced to about 20 dB/km from previous values of more than 1000 dB/km by applying improved fiber manufacturing and design techniques. Since that time, optical communication technology has developed rapidly to achieve larger transmission capacity and longer transmission distance. The capacity of transmission has been increasing about 100 fold in every 10 years.

There were several major technological breakthroughs during the past two decades to achieve such a rapid development. In 1980, the bit rate used was 45 Mb/s with repeater spacing of 10 km. The multimode fiber was used as the transmission medium and GaAs LED as the source of the system. In 1987, the bit rate was increased to 1.7 Gbps with repeater spacing of 50 km. By 1990, the bit rate was increased to 2.5 Gbps with repeater spacing further increased to 60-70 km. Dispersion shifted fibers are used to minimize the bit error rate and to increase the repeater spacing and the bit rate.

In 1996, the bit rate of the optical transmission system was increased to 5 Gbps. The development of optical amplifiers brought another important breakthrough in optical communication system. Optical amplifiers reduced the associated delay and power requirement of the electronic amplifiers. Wavelength Division Multiplexing (WDM) was also introduced at this time to increase the available bandwidth capacity in terms of the channels. By 2002, the bit rate of the optical system was increased to 10 Gbps with repeater spacing of 70-80 km. The introduction of the dense-wavelength division multiplexing (DWDM) system increased the channel capacity and the bit rate increased to 40 Gbps.

1.4 Gigabit Passive Optical Network (GPON)

Gigabit Passive Optical Network (GPON) is an optical technology based on the industry standard ITU-TG.984x which was ratified in 2003. This technology was originally developed to provide high speed Ethernet services for residential and small business customers. It supports higher rates, enhanced security, and choice of Layer 2 protocols (ATM, GEM, and Ethernet). A passive optical network (PON) is a point to-multipoint, fiber to the premises network architecture in which unpowered optical splitters are used to enable a single optical fiber to serve multiple premises, typically 16-128. A PON consists of an optical line terminal (OLT) at the service provider's central office and a number of optical network units (ONTs, ONUs) near end users. A PON reduces the amount of fiber and central office equipment required compared with point-to-point architectures. A passive optical network is a form of fiber-optic access network.

1.5 Evaluation of GPON System

First of all, PON was ATM PON (APON) which evolved in Broadband PON (BPON). BPON is backward compatible with APON. Ethernet PON (EPON and newer GEPON) is alternate solution for PON networks. It is an IEEE standard not compatible with A/BPON.GPON is PON exclusively for Ethernet and IP traffic. GPON and EPON are standardized by the ITU-T and the IEEE. The difference between APON and BPON are the extra overlay capabilities supported by BPON to use video and other Broadband services. The technology used in the BPON standard is called Asynchronous Transfer Mode (ATM). The PON standard is shown as Figure 1.2.

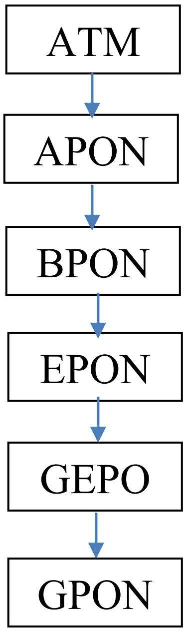


Figure-1.2: GPON Evaluation

The timing requirement of GPON is much rigid than that of EPON. The performance of EPON systems frames are transmitted as a Control frame and Data frames. At the user level, 1 Gb/s is available; on the lower level, due to 8B/10B encoding, the data rate at the fiber is 1.25 Gb/s. BPON was developed as a PON system that uses ATM cells for transmission and has a maximum access speed of 155 Mbit/s upstream and 622 Mbit/s downstream. By using ATM cells, BPON can accommodate various services, such as Internet or Cable TV (CATV) services. The differences between BPON, GPON and EPON can be found at different levels. A BPON system is a good system but more or less replaced by the GPON standard. All the user services provided by BPON can be found in the GPON system as well. GPON is more flexible since it provides not only an ATM service but also additional services like General Encapsulation Method (GEM) with several possibilities for data encapsulation. Like ATM or GEM, Ethernet is capable of encapsulating other protocols. Both BPON and GPON use the ATM protocol, where BPON actually uses it at the network level and GPON only provides a service point for ATM. The network layer of GPON uses its own frame format to transfer the data.

1.6 Challenges against GPON Networks

Currently, South Asian countries are facing various problems when they are planning to deploy GPON. Most of them are shown in Figure-1.3.

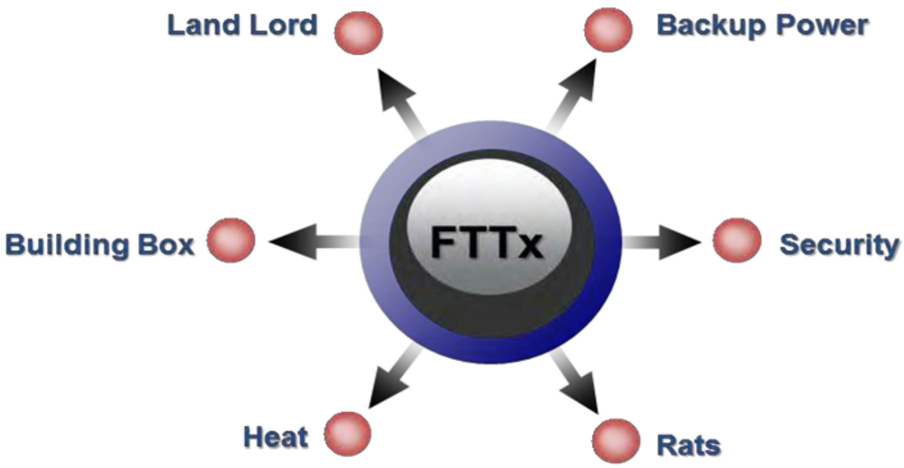


Figure-1.3: FTTx Deployment Problem

Land Lord Problem: Most of the Land Lords do not agree to put ONT in their building premises. Most of them think it as an extra hassle. But, nowadays, awareness is growing and many of them have realized the good sides of GPON technology and some of house owners are willingly request to put BDB in their building premises.

Power Backup Problem: Commercial power backup is another big challenge for FTTH service providers. An ONT consumes very little electrical power. If an ONT is ON 24 hours a day for a month, So, it will cost only 0.60$ to 1$. But in our country, most of house owners/ Land lords do not agree. In Bangladesh, load shading is a regular matter; during load shading client will not be able to get service. But, nowadays, most of the clients get power backup from their own UPS or IPS.
Building Distribution Box Problem: Many land lords are not agreeing to install a BDB in his building. After BDB box installation, sometimes BDB key is broken by thieves or bad peoples.

Security: Security is another concern issue for FTTx Deployment. ONTs, BDBs and sometimes fiber is stolen.

Heat: In case of Asian country like Bangladesh, heat is a major problem for ONTs. Sometimes service providers have to install ONTs in outdoor. After some months, it is damaged due to heat and dust.

Rats: Sometimes patch cords are cut by rats. Practically, Bangladesh has faced this type of problem continuously.

Weak Planning for Deployment: The process of laying fiber involves securing approvals from multiple agencies which is a key challenge. The lack of government intervention in addressing this issue is a major roadblock.

The governments in countries such as Finland, Germany and Singapore, have been instrumental in facilitating the roll-out of FTTH networks. For instance, in Germany, the Munich government has laid an underground duct system, which can be used by all utility service providers including telecom operators to provide services to customers. The Singapore government has made it mandatory for every household to allow access to operators for deploying fiber infrastructure. Such initiatives requiring the involvement of municipal corporations have not been taken in Bangladesh.

To deploy FTTx in Bangladesh there are some other problem like-
- Charges for laying fiber in towns and cities are very high.

-The return on investment in FTTH networks is realized only when a subscriber uses services at the connected location. The returns are impacted when subscribers shift from their locations unlike wireless connections. The FTTH network deployed at premises remains idle until the next user occupies it. Wireless connections allow operators to provide services to customers irrespective of their location.

- The high cost of the related consumer premise equipments and optical network terminals is another challenge. Currently, most of these equipments are imported, which accounts for a significant part of overall costs.

- Other issues include the efficient transportation of the huge bandwidth, selecting the FTTx access mode and design, ensuring quality of experience for multi-play services, fiber resource saving, long distance coverage, reliable fiber transporting and rational planning of the optical distribution network.

- Currently, the RoW within housing projects or resident welfare associations is controlled by the builder, which generally gives access to one or two operators. Rolling out FTTH in these areas is viable for an operator, if it is guaranteed a subscriber base. Otherwise, competition from other operators reduces the maximum penetration an operator can expect.

1.7 Properties of GPON Networks

GPON networks have some properties which are as follows:

1.7.1 Fiber Access Networks

Due to both economical and practical reasons, the significance of broadband communication for the community is growing rapidly triggering an explosion of fiber access network deployments, and consequently providing great business opportunities for both system and network providers.

On the other hand, bandwidth demanding applications, such as high-definition television (HDTV), real-time interactive gaming, telemedicine, broadband Internet service, etc as well as user behaviour (always on) are creating a new challenge of efficiently and flexibly providing ultra-high bandwidth in the access networks.

Several broadband access technologies exist today, such as copper based digital subscriber loop (DSL), wireless and fiber access. However, the fiber access is the only viable technology for the future access networks [1-5]. Fiber-to-the-home (FTTH) is the future-proof technology offering ultra-high bandwidth and long reach. Several fiber access network architectures have been developed, e.g., point-to-point (P2P), active optical network (AON) [6] and passive optical network (PON) [7-11]. However, PON is considered as the most promising solution due to the relatively low deployment cost and resource efficiency. Furthermore, based on two resource sharing technologies of time-division multiplexing (TDM) and wavelength-division multiplexing (WDM), there are three main types of PONs, namely TDM PON, WDM PON and hybrid WDM/TDM PON.

1.7.2 Switched Optical Networks

The concept of optical transparency is widely discussed. Transparency refers to the property of an optical network to show independence with respect to a number of characteristics, such as bit rate, protocol, and modulation format. Optical transparent networks, based on WDM technology, seem to be the most promising candidates for future high capacity long-distance communication. In such networks, switching functions will be carried out directly in the optical domain so that high speed optical signals can travel through the network without any optical-to-electrical conversion. Different switching paradigms can be applied to exploit the optical technology in terms of different switching granularities. These are:

- Optical circuit switching
- Optical burst switching
- Optical packet switching

1.7.2.1 Optical Circuit Switching

Circuit switching has been used in telephone networks for a long time. In this classical approach, a physical circuit is established for the complete duration of the connection from the source to the destination and the reserved resources cannot be shared. The traditional (electronic) circuit switching can be performed by space switching, time switching or usually a combination of both. The optical circuit switching (OCS) paradigm (mostly at wavelength level) is a technique to offer huge bandwidth in the backbone part of the network [12]. This approach provides access to bandwidth with a coarse granularity. An OCS network can also be referred to as wavelength routed network. It provides end-to-end optical channels (light paths) between source and destination nodes. Light path can be set up and torn down on request. One of the most important challenges is solving routing and wavelength assignment (RWA) problem, which consists of finding a suitable physical route for each light path request, and assigning an available wavelength to that route. Demands to set up light paths may be known in advance and set up semi-permanently (static or off-line), or can arrive in a stochastic manner with random holding times (dynamic or on-line). In the static case, the common objective of RWA is to minimize the resources (such as number of wavelengths or number of fibres) that will be needed to support all the light paths in the network, while in the dynamic scenario light path blocking probability is a major performance characteristic. A suitable OCS node (referred to as optical cross connect OXC) architecture can significantly improve the blocking performance.

1.7.2.2 Optical Burst Switching

In contrast to OCS, optical burst switching (OBS) is based on statistical multiplexing, which can increase the efficiency of network resource utilization. OBS networks mainly consist of two types of switching nodes, namely edge and core nodes. The edge node can aggregate client data, e.g., Internet protocol (IP) packets into bursts. Each burst has an associated control packet. Usually, a burst is separated from the control packet by the interval of offset time. The main functions of the edge nodes are assembly/disassembly of optical burst, and decision of offset time and burst size. The OBS core nodes perform control packet lookup, optical cross connecting and data burst monitoring. Compared with the edge nodes, the core nodes can have relatively simple structure.

1.7.2.3 Optical Packet Switching

In optical packet switching (OPS), packets are buffered and routed in the optical domain. OPS may become a competitive solution in the future for the high capacity wide-area networks. In contrast to OCS and OBS, OPS networks have the switching granularity on the packets level, and can realize most flexible and efficient bandwidth management. The functionality of OPS node should include: decoding packet header, (can be electronic if the packet header is encoded at lower bit rates), configuring a switch fabric (the reconfiguration needs to be performed very fast in nanosecond range), synchronization (for synchronous OPS nodes), multiplexing, and contention resolution. A lot of existing research has focused on the architecture design of OPS nodes with efficient contention resolutions.

1.7.3 Triple Play Service

Triple Play service allows providing voice, video and data in a single access subscription. The most common applications are Telephony, TV and high-speed Internet access.
The proposed bandwidths which have been used for the different applications :
• VoIP: For voice over IP is needed 15Kbps with G.723 voice codec.
• TV: For television, we use 8Mbps for high definition channel and 1,5Mbps for standard definition channel with MPEG4 compression.
• Internet Access: we use from 6Mbps up to 10Mbps for downstream and 1Mbps for upstream.

1.8 Related Research Work

Over the years, a lot of research works have been carried out to study the GPON network structure and different type of FTTx model. Some of them are discussed below.

A.M.J. Koonen et al. (2006) reviewed Fiber-optic technologies which enable cost-effective delivery of broadband services to users in multiple-access network architectures [12]. He also described that the dynamic network reconfiguration can optimize system performance, in particular, for roaming traffic loads such as in fiber-wireless networks.

Yong-Hun Oh et al. (2007) have described a fully integrated burst-mode upstream transmitter chip for gigabit-class passive optical network applications and was implemented in 0.18μm CMOS technology [13]. In order to control consecutive burst data, the transmitter proposed to use a reset mechanism with TX_enable as a burst envelope signal. The feedback from the monitoring photodiode (MPD) is separated by two independent paths for temperature compensation. The chip tested with chip-on-board configuration shows an average power of 2dBm with extinction ratio of above 12dB under 1.25Gb/s burst mode operation. Based on the measurement, their work complied with the GPON ITU-T Recommendation G.984.2.

Ivica Cale et al. (2007) theoretically described that a new service like Television (IPTV) and Video on demand (VoD) over Internet together with High Speed Internet access (HSI) have demand for very high bandwidth to customers [14]. XDSL have some form which can satisfy bandwidth demand (VDSL2) but have restriction regarding distance. Probably only suitable solution for high bandwidth demand with a long reach is using optical cable to customers (FTTx). One of the ways they have discussed using some type of Passive Optical Network (PON). Gigabit PON (GPON) is the most often type used by European and US providers (in addition with APON and BPON) while providers in Asia predominantly use EPON/GePON. Mainly they focused on an overview of Gigabit PON and analyzes network architecture, transmission mechanisms and power budget in GPON systems.

Derek Nesset et al. (2008) have simulated GPON System with a 1300 nm semiconductor optical amplifier which was developed for extended reach GPON applications [15]. The high gain of 29dB has enabled a commercial GPON system to operate over 60 km and with 128-way split.

Attila Mitcsenkov et al. (2009) have addressed on broadband optical access network design minimizing deployment costs, taking operation issues into account, using detailed cost and network models of the above listed FTTx technologies that suit best to actual networks due to detailed cost metrics used instead of just minimizing fiber lengths [16]. They presented a heuristic solution that works fast even for large problem instances, providing results with a difference less than approximately 10-20% from the computed Integer Linear Programming (ILP) optimum for smaller cases where ILP could be used. Along with those algorithms they present case studies of real-life network and service requirement instances.

Faruk Selmanovic et al. (2010) has provided a relation between GPON and NG Network. They have tryed to show that Gigabit Passive Optical Networks are very economical, effective, and reliable solution for triple play service [17]. Also, they showed GPON as technical and economical sound solution for Next Generation Network. They present details about GPON applications such as: GPON ONU as Uplink, GPON as metro net, multi-user per one GPON ONU, GPON as FTTH/B, etc. They mention mechanisms that are used for implementing GPON applications such as: DBA algorithm (algorithm for control of upstream speed), GEM (inner transmit method), protection schemes, and control of download speed as additional feature that is not included in the default GPON settings. Briefly, they look at other elements of GPON such as aggregation switch; voice service: V.5.2, SIP and H.248. Economic aspect of projects and/or solutions in telecommunication networks is very important factor; GPON is no exception. So, they try to present both economical and technical aspects of GPON in relation to telecommunication network, and other similar solution that are currently available.

Claudio Rodrigues et al. (2011) have reviewed and compare the current gigabit passive optical networks (GPON) fibre to the home (FTTH) based solution, and discussed an evolution scenario to future next generation PONs (XGPONs) and wavelength division multiplexing PONs (WDM-PONs) from an operator point-of-view, i.e., taking into account standardization, wavelength planning, optical line terminal as well as optical network terminal equipment and transmission convergence layer [18]. They also compare a proposed architecture for the provision of quintuple play services over orthogonal frequency division multiplexing (OFDM) in several aspects such as equipment requirements, capacity to the end user and limitations.

Marcelo Alves Guimaraes et al. (2011) have proposed a new technique for transmitting E1 streams in a more efficient bandwidth allocation scheme, by fragmenting E1 signals without using circuit emulation techniques [19]. It is based on the combination of spatial and temporal switching, has been simulated in a hardware description language (HDL) platform and the results demonstrate the potential use of the technique in GPON equipment.

Mazin Al Noor et al. (2012) discussed about analoge and digital signal transmission utilizing GPON-CWDM based RoF over long distance [20]. Optical-wireless access technologies have been considered the most promising solution to achieve effective delivery of wireless and baseband signals. They increase the bandwidth and extend the transmission distance at a lower budget and environmentally friendly. The means to accomplish this aim is to simplify the design by GPON via radio over fibre (RoF), which is able to provide much higher total bandwidth at a longer connection distance. The integration of an 18 channel coarse wavelength division multiplexing (CWDM) in the GPON, allows the use of less expensive, un-cooled lasers, operating with reduced energy consumption. They demonstrate the deployment of a combined wireless system, 3.5GHz WiMAX, 2.6GHz LTE and baseband signals with a bit rate of 2.5Gbps downlink and 1.25Gbps uplink in GPON-CWDM via RoF technology. The signals are transmitted to the bidirectional splitter-32 for 160km bidirectional SMF length and from the splitter to WDM-DEMUX for 50km SMF length. The CDF and CFBG are utilized to increase signal transmissions distance. As a result, they achieve an extension of the transmission distance to 600km. Furthermore, the results indicate open eye diagrams, a clear RF and bandwidth spectrum and consultation diagram as well as low-energy consumption; Q-factor, SNR and OSNR have improved.

Andrej Chu et al. (2013) proposed a solution by using ant colony optimization to design GPON-FTTH networks with aggregating equipment [21]. With the huge demands for the provision of inexpensive and fast broadband services, GPON has been considered to be the most attractive solution for providing broadband access network. However, due to the consideration of many design factors such as the number, types, positions of network elements and routing information, the optical network planning process often exhibits several challenges from the optimization point of view. This problem is generally NP-hard and cannot be solved in polynomial time by any currently known algorithms. They presented an algorithm based on the Ant Colony Optimization (ACO) method with dedicated post processing. Given a geographical location of a Greenfield area, proposed solution minimizes the overall GPON network deployment cost by selecting the optimum type of aggregating equipment, routing information and cost-effective locations of network elements. In the result section, different network examples are provided to illustrate the effectiveness of the ACO approach for this type of problem.

Rastislav Roka et al. (2014) analysed possible exploitation for long reach passive optical networks [22]. For the expansion of networks based on optical transmission media, it is necessary to have a detailed knowledge of advanced implementations for passive optical systems used in the access network. This contribution shortly discusses possible scenarios of exploitation for hybrid passive optical networks. A main part is focused on characteristics of the GPON network simulation environment and on results from simulation experiments related to the Long Reach Passive Optical Network effective utilization for various higher layers.

M. Irfan Anis et al. (2015) simulated an evaluation of 2.5Gbps bi directional GPON based FTTH link using advanced modulation formats [23]. GPON is a promising solution for increasing bandwidth requirements of customers which supports triple play services and is being considered as a solution for mobile back haul network. It also enables the delivery of cloud services with a high interconnection speed. The performance of the proposed system was studied when a single wavelength and two wavelengths were used for triple-play services with different modulation schemes. They aimed to provide a comparison of the performance of different modulation formats for GPON based simulation of an actual architecture considering Q factor, BER, optical power and OSNR.

From the above discussion and literature review, we observed that there is no detail analysis regarding the convergence of E1 traffic with existing triple play considering some important parameters like power budget, sensitivity threshold, output signal spectrum and transmission wavelength. In this work, a quad play GPON architecture will be designed and developed to exploit the full potential of GPON and to extend its last mile quality of service.

1.9 Motivations

The rapid growth of bandwidth requirements and the changing role of enterprises are causing disruptive change in the enterprises local area networking. The most suitable solution to satisfy the high bandwidth demand and to reduce the total cost of ownership with a long reach is through gigabit passive optical (GPON) technology [1-2]. ITU-T G.984.x recommendations provide GPON system model and does not require any electrical power at the intermediate nodes between the aggregation and user nodes [3]. In the last one decade, many research works had been carried out on network architecture, transmission mechanisms, power budget, bandwidth allocation and scalability of GPON technology [4-6]. Bandwidth allocation schemes, quality of triple play service in IP network and passive optical local area network are discussed in [7-8]. Ricciardi, S. et al. have shown an analysis and comparison between Ethernet point to point and GPON connectivity [9]. Nusantara, H. et al. have analyzed the design of fiber access network systems using GEPON technology for high rise building considering both for power and rise time budget standard as well as cost for the deployment of a passive optical fiber at the home network is calculated in terms of net present value, internal rate of return and payback period [10-11]. There is a scope to analyzes in detail regarding the convergence of E1 traffic with existing triple play considering some important parameters like power budget, sensitivity threshold, output signal spectrum and transmission wavelength. In this research, a quad play GPON architecture will be designed and developed to exploit the full potential of GPON and to extend its last mile quality of service.

1.10 Objectives

In telecom sector, it is very much important to deploy a solution for its clients which will be cheap, secure and user-friendly. The main goal of this work is to find a new architecture for supporting better data rates and additional services through time division multiplexing. To achieve the goal, the main objectives of this research are:

i) Design and analysis of a quad play architecture for GPON system without Erbium doped fiber amplifier combiner.

ii) Determine a fixed wavelength for better sensitivity for relatively long-distance connectivity.

iii) Performance analysis of the proposed quad play GPON architecture.

iv) Comparing the results with the existence literatures.

1.11 Methodology

A passive optical network is a point-to-multipoint, fiber to the premises network architecture in which unpowered optical splitters are used to enable a single optical fiber to serve multiple premises, typically 16-128. The research work has been carried out in the following sequence:

i) We have designed a fiber to home quad play architecture with combination of E1 traffic and analyzed the output signals at end user site. Here, direct modulated laser has been used as source instead of Erbium doped fiber amplifier combiner or video signal combiner.

ii) We have designed optical line terminal block (i. e. transmitter block) using OptSim of Rsoft simulation software which consists of data/VoIP and video components. The data/VoIP transmitter is modeled with pseudo-random data generator, non-returned to zero modulator driver, direct-modulated laser, and booster amplifier. The video component is modeled as RF sub-currier multiplexed (SCM) link with only two tones (channels).

iii) Next, we have designed a data/voice and video signals unit which is multiplexed and launched into 20-Km fiber span. Output from the fiber trunk goes through the 1:16 splitter and then to individual users. User's optical network terminal consists of splitter and data and video receivers.

iv) Next, we have worked to select an optimum wavelength, which has increased the triple play performance and improve the network performance as a whole.

v) Finally, we have simulated the performance of developed GPON FTTH quad play scenario using simulator and analyzed the output signals at the best wavelength and also compare with the existing triple play architectures.

1.12 Outline of Research

In this section, we present chapter wise overall outline of our thesis.

Chapter 2 is about GPON Technology where mentioned basic concepts of GPON Technology, how GPON technology works, GPON enhancing with respect to world telcos and also with respect to Bangladesh and a brief idea regarding any time any service by GPON technology are discussed.

Chapter 3 is about the property analysis of DWDM and CWDM GPON. Various calculated parameters are discussed in this chapter.

Chapter 4 presents the analytical analysis of BER, Power penalty, Crosstalk analysis and shares sample sensitivity calculation.

Chapter 5 discusses the simulation environment and results. The results are analysed in this chapter.

And finally, the Chapter 6 is my conclusion part where I gave some opinion and also shared my idea for future research.

1.13 Summary

In this chapter, GPON technology's background, problems to deploy GPON technology, properties of GPON technology, my objective, methodology and also outline of this thesis paper are discussed. In GPON networks there are some infrastructures such as OLTs, ODFs, Splitters and ONT/ONUs.

To implement triple play, it is very much important to choose technology. GPON technology is better than any other technologies like EPON, APON, BPON, GEPON P2P Ethernet, etc. To secure GPON network, it has been considered the following attributes: availability, confidentiality, integrity, authentication, and non-repudiation. Deploying GPON technology by FTTx network is still a challenging issue. But, nowadays the whole world is going to deploy GPON technology.

Chapter 2

GPON Technology: An Overview

Gigabit Passive Optical Network (GPON) is an optical technology based on the industry standard ITU-TG.984x which was ratified in mid 90s [3]. This technology was originally developed to provide high speed Ethernet services for residential and small business customers. It supports higher rates, enhanced security, and choice of Layer 2 protocol (ATM, GEM, Ethernet). A **passive optical network** (**PON**) is a point-to-multipoint, fiber to the premises network architecture in which unpowered optical splitters are used to enable a single optical fiber to serve multiple premises, typically 16-128. A PON consists of an optical line terminal (OLT) at the service provider's central office and a number of optical network units (ONTs, ONUs) near end users. A PON reduces the amount of fiber and central office equipment required compared with point-to-point architectures. A passive optical network is a form of fiber-optic access network.

2.1 Introduction to GPON

GPON is a point-to-multipoint access mechanism. Its main characteristic is the use of passive splitters in the fiber distribution network, enabling one single feeding fiber from the provider's central office to serve multiple homes and small businesses. The GPON standard differs from other PON standards in that it achieves higher bandwidth and higher efficiency using larger, variable-length packets. GPON offers efficient packaging of user traffic, with frame segmentation allowing higher quality of service (QoS) for delay-sensitive voice and video communications traffic.

The main objective of this chapter is to give an overview of GPON technology. The focus of the discussion is how GPON technology works and how it is enhancing.

2.2 How GPON Technology Works

GPON has a downstream capacity of 2.488 Gbits/s and an upstream capacity of 1.244 Gbits/s that is shared among users. Encryption is used to keep each user's data secured and private from other users. Although there are other technologies that could provide fiber to the home, passive optical networks (PONs) like GPON are generally considered the strongest candidate for widespread deployments. GPON does broadcast to its downstream [14].

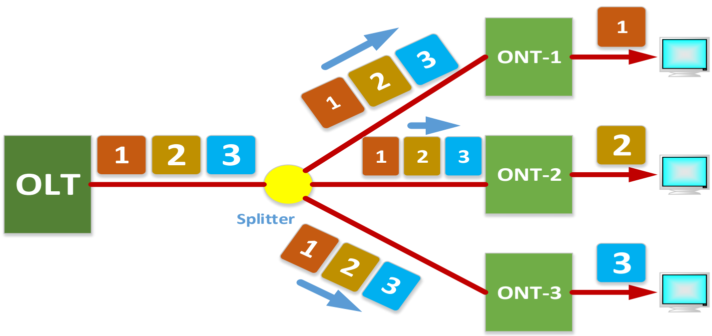


Figure-2.1: GPON Broadcasting to Downstream.

The operating wavelength range is 1480-1500 nm for the downstream and 1260-1360 for upstream. It provides unprecedented bandwidth (shared by up to 128 premises), and a greater distance from a central office (20 to 40 kilometres), allowing service providers to enable bandwidth-intensive applications and establish a long-term strategic position in the broadband market. Enterprise GPON is also a carrier class technology that provides a high level of Quality of Service (QOS) of 99.999% for those customers with mission-critical requirements. GPON manufacturers are now working on devises that will allow up to 10Gbs on bandwidth. GPON works to its upstream by using Time Division Multiple Access (TDMA) [14].

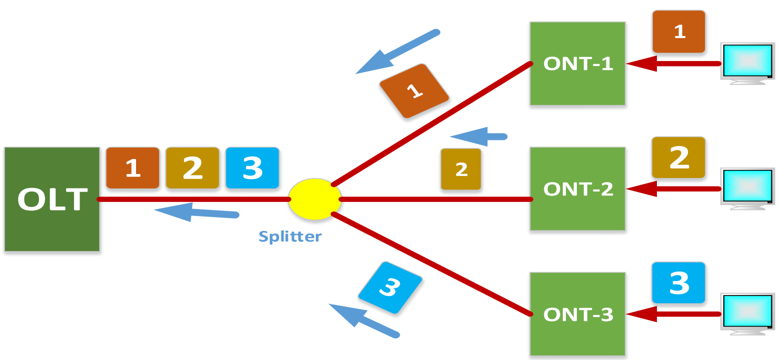


Figure-2.2: GPON TDMA to Upstream.

As a result, a new standard known as G987 or also known at 10-PON has 10 Gbit/s downstream and 2.5 Gbit/s upstream – framing is "G-PON like" and designed to coexist with GPON devices on the same network. This is great news for data network managers looking for low-cost, high-bandwidth, networking technologies in order to keep up with the demands on data applications and growth including "cloud" services. By GPON Technology, service provider could provide several services to its customers like- IP TV, Voice (VoIP), Video, Data Connectivity, Internet connectivity, value added service (Online gaming, Social networking, Video on Demand, etc) and other services.

2.3 Any Time Any Service by GPON

The provisioning of GPON IP based video services is implemented by electronic program guide (EPG)/content portal. When an STB starts and passes authentication. With the address, it accesses the video system to perform software load and user authentication. When it passes user authentication, the video management system will send an EPG according to his/her rights and service subscription. EPG is portal pages through which the subscriber can select services. There are many ways to acquire an EPG with assistance from the client on an STB and EPG/portal server. For BTV services, an EPG should offer necessary multicast session information such as multicast address, port no., media type, and coding scheme. Coding schemes for IPTV programs include the MPEG2, MPEG4, and WMV. The MPEG2 provides ordinary video quality at a code rate of 2 Mbit/s and broadcasting-class video quality at a rate of 3.5 Mbit/s. The MPEG-4 enables high video quality at a rate of 1.5 Mbit/s while H.264 can provide more video services with higher definition at rates below 1 Mbit/s. Video streams are delivered using MPEG over IP [14]. Multicast video streams coming from the coder and video server are directly output to core network and then sent to subscribers via a FTTP access network. IPTV that is already been emerged with many IP based broadband services, is continuously evolving and changing. At the same time, service providers' networks have different needs depending on markets, distribution areas, plant and density. Increasingly, service providers need access platforms to launch service from different points in the network, to utilize different copper or fiber facilities, and to incorporate more quality and performance with the services offered. Adaptability becomes an important aspect for access to meet a variety of needs, with the choice in the hands of the service provider rather than dictated by the limitations of technology.

GPON optical network terminal (ONT) provides support for high speed data and high definition IPTV service with Gigabit Ethernet ports. It is a cost-effective solution for point to multipoint scenarios where passive optical splitters are used to allow a single optical fiber for providing multiple premises. IPTV delivers video services based on IP multicast. At the source end, different program, sources are configured with different multicast address, and reach the ONU device through a series of broadcast service. Effective broadcast IPTV service requires extensive bandwidth and the support of IP multicast and IGMP. For deployments requiring open access or other multiple broadcast sources, these can be provisioned on VLAN basis. Thus, through IGMP and IP multicast, the ONT model provides full support for broadcast IPTV services with VLAN capability supporting open access IPTV solutions. The large bandwidth available on such GPON ONTs enables them to transparent transport all video encoding standards, including MPEG-2 and MPEG-4. In example, if each ONT supports over 256 multicasts MPEG-2 video channels con-currently, then that is capable to provide virtually unlimited video streams support with unicast MPEG-2. Additionally, some ONTs are ide-ally suited to support VoD, PPV and other IPTV related packet-based services desired today by numerous networks.

Currently, Bangladesh is offering multiservice in a single ONT like Data connectivity, VoIP, and Internet connectivity. Bangladesh is ready to provide IPTV, Online gaming and video on demand (VoD).

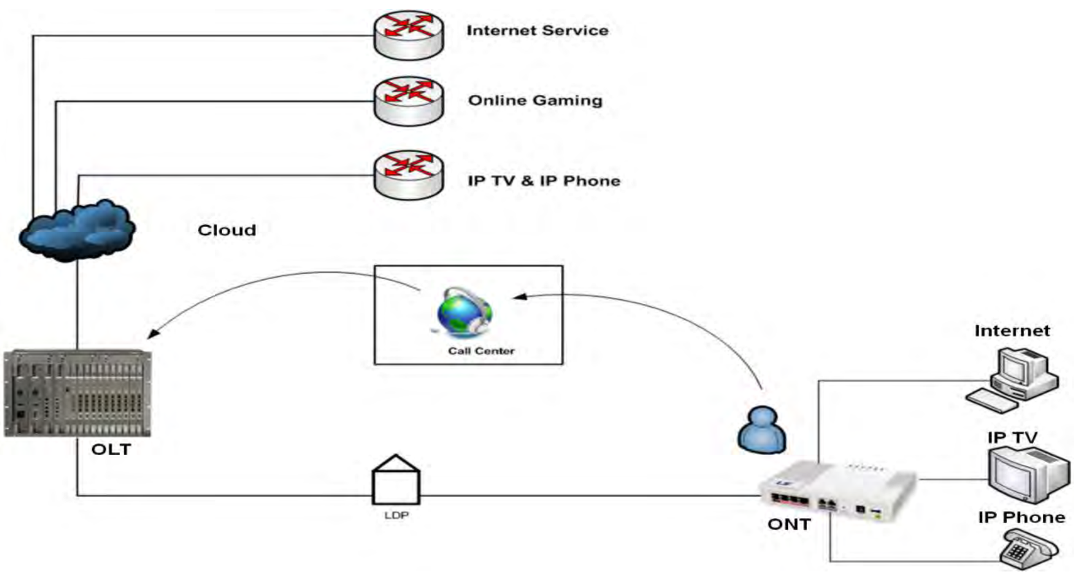


Figure-2.3: Triple Play Service by GPON

2.4 GPON Interoperability Problems

One of the challenges of the market of high-speed access is the price per subscriber. The economic advantages of PON type deployment have presented, but we must bear in mind another point: The cost of the ONT or terminal client.

With the aim of reducing the price of the ONT, it is important that any OLT is able to interact with any ONT regardless of manufacturer. However, GPON has a number of characteristics that may make the interoperability of manufacturers difficult for any of the following reasons:

· **Commercial implementations from earlier versions of the standard:** Although it is now in a very mature state, there is still no final version of the standard. This has led to "early adopters" manufacturers to have implemented versions of the standard that may differ greatly from the current one.

· **Temporal complexity of the negotiation process**: The processes of detection and ranging are very sensitive. A delay or advancement of microseconds can cause both equipment not to trade.

· **Misinterpretation of the standard**: GPON standard is complex and has undergone major changes. It is easy for different manufacturers to interpret the standard differently causing problems in negotiations.

· **OMCI, a very broad standard**: OMC management layer is designed to remotely configure all the functionality of an ONT. In addition, the standard defines a very broad set of OMCI entities that can be combined in various ways to establish the same services. Two manufacturers may be able to offer the same services but using different GPON OMCI entities.

· **Heterogeneity among operators**: Each carrier deploying a GPON solution selects a subset of OMCI to deploy their services; this means GPON custom hardware implementations of the specific OMCI layer for each operator.

As can be inferred, **interoperability is an important requirement in any GPON network**. When **problems of interoperability** appear, identification of the causes is a difficult diagnostic challenge that usually requires a source of information and analysis beyond the GPON hardware manufacturers affected.

2.5 Summary

In this section, general discussion of GPON technology, GPON enhancing and a brief idea regarding any time any service or triple play service have been discussed. Interoperability problem for GPON is also discussed.

Currently in Bangladesh, GPON technology users are growing rapidly. They have enjoyed the good flavour of GPON and now most of users are demanding for triple play service, like-IP phone, and IP TV/Digital TV and Internet connectivity. Some value-added service like-Online Gaming, Video on demand and social networking are also increasing demand.

Chapter 3

Properties Analysis of DWDM and CWDM GPON

3.1 Introduction

A PON takes advantage of wavelength division multiplexing (WDM), using one wavelength for downstream traffic and another for upstream traffic on a single non-zero dispersion-shifted fiber (ITU-T G.652). BPON, EPON, GEPON, and GPON have the same basic wavelength plan and use the 1490 nano meter (nm) wavelength for downstream traffic and 1,310 nm wavelength for upstream traffic. 1,550 nm is reserved for optional overlay services, typically RF (analog) video.

As with bit rate, the standards describe several optical budgets, most common is 28 dB of loss budget for both BPON and GPON, but products have been announced using less expensive optics as well. 28 dB corresponds to about 20 km with a 32-way split. Forward error correction (FEC) may provide another 2–3 dB of loss budget on GPON systems. As optics improve, the 28 dB budget will likely increase. Although both the GPON and EPON protocols permit large split ratios (up to 128 subscribers for GPON, up to 32,768 for EPON), in practice most PONs are deployed with a split ratio of 1x32 or smaller.

The access network, also known as the "first-mile network," connects the service provider central offices (COs) to businesses and residential subscribers. This network is also referred to in the literature as the subscriber access network, or the local loop. The bandwidth demand in the access network has been increasing rapidly over the past several years. Residential subscribers demand first-mile access solutions that have high bandwidth and offer media-rich services. Similarly, corporate users demand broadband infrastructure through which they can connect their local-area networks to the Internet backbone.

The predominant broadband access solutions deployed today are the digital subscriber line (DSL) and community antenna television (CATV) (cable TV) based networks. However, both of these technologies have limitations because they are based on infrastructure that was originally built for carrying voice and analog TV signals, respectively; but their retrofitted versions to carry data are not optimal. Currently deployed blends of asymmetric DSL (ADSL) technologies provide 1.5 Mbits/s of downstream bandwidth and 128 Kbits/s of upstream bandwidth at best. Moreover, the distance of any DSL subscriber to a CO must be less than 18000 ft because of signal distortions. Although variations of DSL such as very-high-bit-rate DSL (VDSL), which can support up to 50 Mbits/s of downstream bandwidth, are gradually emerging, these technologies have much more severe distance limitations.

For example, the maximum distance over which VDSL can be supported is limited to 1500 ft. CATV networks provide Internet services by dedicating some radio frequency (RF) channels in a coaxial cable for data. However, CATV networks are mainly built for delivering broadcast services, so they don't fit well for the bidirectional communication model of a data network. At high load, the network's performance is usually frustrating to end users.

Passive optical networks (PONs) have evolved to provide much higher bandwidth in the access network. A PON is a point-to-multipoint optical network, where an optical line terminal (OLT) at the CO is connected to many optical network units (ONUs) at remote nodes through one or multiple 1:N optical splitters. The network between the OLT and the ONU is passive, i.e., it does not require any power supply.

PONs use a single wavelength in each of the two directions—downstream (CO to end users) and upstream (end users to CO)—and the wavelengths are multiplexed on the same fiber through coarse WDM (CWDM). For example, the Ethernet PON (EPON) uses 1490 nm wavelength for downstream traffic and the 1310 nm wavelength for upstream traffic. Thus, the bandwidth available in a single wavelength is shared amongst all end users. Such a solution was envisaged primarily to keep the cost of the access network low and economically feasible for subscribers. Various blends of the PON have emerged in recent years: the Ethernet PON (EPON) is a relatively recent version that is standardized in the IEEE 802.3ah [1], the broadband PON (BPON) is standardized in the ITU-T G.983, and the generic framing procedure based PON (GFP PON) is standardized in the ITU-T G.984. An enhancement of the PON supports an additional downstream wavelength, which may be used to carry video and CATV services separately. Many telecom operators are considering to deploy PONs using a fiber-to-the-x (FTTx) model (where x = building (B), curb (C), home (H), premises (P), etc.) to support converged Internet protocol (IP) video, voice, and data services—defined as "triple play"—at a cheaper subscription cost than the cumulative of the above services deployed separately. PONs are in the initial stages of deployment in many parts of the world. Although the PON provides higher bandwidth than traditional copper-based access networks, there exists the need for further increasing the bandwidth of the PON by employing wavelength-division multiplexing (WDM) so that multiple wavelengths may be supported in either or both upstream and downstream directions. Such a PON is known as a WDM-PON. Interestingly, architectures for WDM-PONs have been proposed as early as the mid-1990s. However, these ideas have not been commercialized yet for many reasons: lack of an available market requiring high bandwidth, immature device technologies, and a lack of suitable network protocols and software to support the architecture. We believe that many of the above factors have been mitigated over the years, and WDM-PONs will soon be viable for commercial deployment.

3.2 GPON Triple Play Present Structure by DWDM Technology

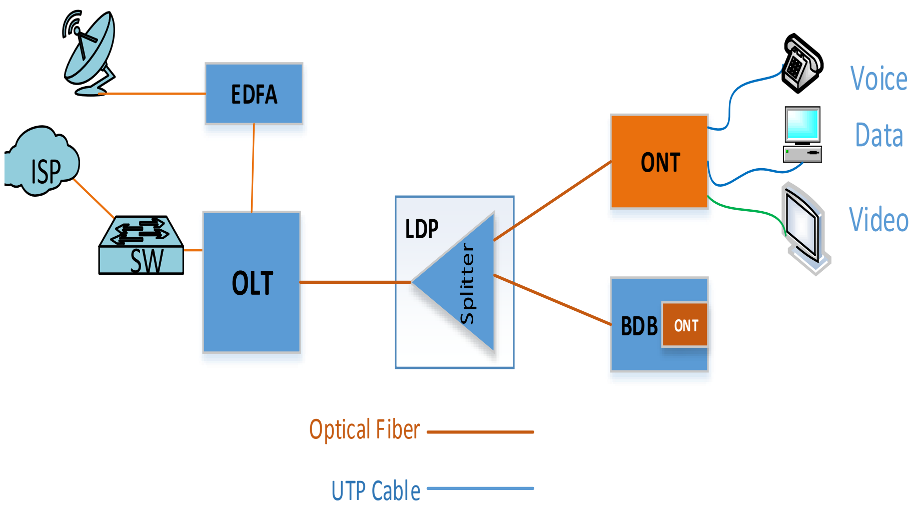


Figure-3.1: Traditional triple play architecture

The video signal enters to OLT through EDFA and the ISP connection for Data and Voice enter via a layer-2 switch. The OLT passed the modulated signal through fiber, optical splitter and finally from ONT's ethernet port, the user receives the signal.

Dense Wavelength Division Multiplexing (DWDM) is an optical multiplexing technology used to increase bandwidth over existing fiber networks. DWDM works by combining and transmitting multiple signals simultaneously at different wavelengths on the same fiber. The technology creates multiple virtual fibers, thus multiplying the capacity of the physical medium. DWDM is a fiber optic transmission technique that allows the transmission of a variety of information over the optical layer. The DWDM uses dispersion-flattened fibers where the dispersion weakly depends on operating wavelength. DWDM technology is efficiently used for increasing the capacity and reliability of fiber optic communication systems. Unlike previous generation optical networks, where the information is carried by a single light beam, DWDM carves up large bandwidth of an optical fiber into many wavelength channels making spectral band use more efficient. Each of the optical carrier's wavelength carries information individually but their spacing needs to be properly chosen to avoid inter-channel interference. DWDM can increase the information carrying capacity by about 10-100 times without the need of a new optical fiber.

DWDM systems are also bit rate and format independent and can accept any combination of interference rates on the same fiber at the same time. This technology can be applied to different areas in the telecommunications networks, that includes the backbone networks, the residential access networks and also local area networks.

3.2.1 Key points of DWDM:

(i) DWDM optical systems require a thermoelectric cooler to stabilize the wavelength emission and absorb the power dissipated by the laser.
(ii) This consumes power while adding cost.
(iii) For short transmission distances, a 'coarse' wavelength grid can reduce terminal costs by eliminating the temperature control and allowing the emitted wavelengths to drift with ambient temperature changes.

3.2.2 DWDM System Advantages

1) Less fiber cores to transmit and receive high capacity data.
2) A single core fiber cable be could have divided into multiple channels instead of using 12 fiber cores.

3) Easy network expansion, especially for limited fiber resource; no need extra fiber but add wavelength. Low cost for expansion, because no need to replace many components such as optical amplifiers, can move to STM-64 when economics improve.
4) DWDM systems capable of longer span lengths, TDM approach using STM-64 is more costly and more susceptible to chromatic and polarization mode dispersion.

3.2.3 DWDM Disadvantages

1) Not cost-effective for low channels; low channel recommends CWDM
2) Complicated transmitters and receivers
3) Wide-band channel; CAPEX and OPEX high
4) The frequency domain involved in the network design and management, increases the difficulty for implementation.

3.2.4 Different Parameter of Calculations to compare CWDM with DWMD

3.2.4.1 Bit Error Rate

The bit error rate (BER) is the number of erroneous bit to the total transmitted bits at the receiver that have been altered due to noise, interference and/or distortion. The modulated signals are transmitted over the optical fiber where they undergo attenuation and dispersion, have noise added to them from optical amplifiers and sustain a variety of other impairments. At the receiver, the transmitted data must be recovered with an acceptable BER. The required BER for high-speed optical communication systems today is in the range of 10^{-9} – 10^{-15}, with a typical value of 10^{-12}. A BER of 10^{-12} corresponds to one allowed bit error for every terabit of data transmitted on average.

3.2.4.2 Bit Error Rate of an Ideal Receiver

In principle, the demodulation process can be quite simple. Ideally, it can be viewed as "photon counting," which is the viewpoint we will take in this section. In practice, there are various impairments that are not accounted for by this model and we discuss them in the next section.

The receiver looks for the presence or absence of light during a bit interval. If no light is seen, it infers that a 0 bit was transmitted and if any light is seen, it infers that a 1 bit was transmitted. This is called *direct detection.* Unfortunately, even in the absence of other forms of noise, this will not lead to an ideal error-free system because of the random nature of photon arrivals at the receiver. A light signal arriving with power P can be thought of as a stream of photons arriving at average rate P/hf_c. Here, h is Planck's constant (6.63 x 10^{-34} J/Hz), f_c is the carrier frequency and hf_c is the energy of a single photon. This stream can be thought of as a Poisson random process.

Note that our simple receiver does not make any errors when a 0 bit is transmitted. However, when a 1 bit is transmitted, the receiver may decide that a 0 bit was transmitted if no photons were received during that bit interval. If B denotes the bit rate, then the probability that n photons are received during a bit interval $1/B$ is given by-

$$e^{-(p/hf_cB)} \frac{\left(\frac{p}{hf_c B}\right)^n}{n!}.$$

Thus, the probability of not receiving any photons is $e^{-(p/hf_cB)}$. Assuming equally likely ls and 0s, the bit error rate of this ideal receiver would be given as

$$BER = \frac{1}{2} e^{-\frac{p}{hf_cB}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Let $M = P/hf_cB$. The parameter M represents the average number of photons received during a 1 bit. Then, the bit error rate can be expressed as

$$BER = \frac{1}{2} e^{-M} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

This expression represents the error rate of an ideal receiver and is called the *quantum limit.* To get a bit error rate of 10^{-12}, we would need an average of M = 27 photons per 1 bit.

In practice, most receivers are not ideal and their performance is not as good as that of the ideal receiver because they must contend with various other forms of noise, as we shall soon see.

3.2.4.3 Bit Error Rate of a Practical Direct Detection Receiver

The optical signal at the receiver is first photo detected to convert it into an electrical current. The main complication in recovering the transmitted bit is that in addition to the photocurrent due to the signal there are usually three others additional noise currents. The first is the *thermal* *noise* current due to the random motion of electrons that is always present at any finite temperature. The second is the *shot noise* current due to the random distribution of the electrons generated by the photodetection process even when the input light intensity is constant. The shot noise current, unlike the thermal noise current, is not added to the generated photocurrent but is merely a convenient representation of the variability in the generated photocurrent as a separate component. The third source of noise is the spontaneous emission due to optical amplifiers that may be used between the source and the photodetector.

The thermal noise current in a resistor R at temperature T can be modeled as a Gaussian random process with zero mean and autocorrelation function $(4k_BT/R)\delta(\tau)$. Here, k_B is Boltzmann's constant and has the value 1.38 x 10^{-23} J/^{0}K and $\delta(\tau)$ is the Dirac delta function, defined as $\delta(\tau)=0$, $\tau \neq 0$ and $\int_{-\infty}^{\infty} \delta(\tau) d\tau = 1$. Thus, the noise is white and in a bandwidth or frequency range B_e, the thermal noise current has the variance

$$\sigma^2_{thermal} = (4k_B T / R) B_e \quad \text{……………………………….. (3.3)}$$

This value can be expressed as $I_t^2 B_e$, where I_t is the parameter used to specify the current standard deviation in units of $pA/\sqrt{Hz}$. Typical values are of the order of $1\, pA/\sqrt{Hz}$.

The electrical bandwidth of the receiver, B_e, is chosen based on the bit rate of the signal. In practice, B_e varies from $1/2T$ to $1/T$, where T is the bit period. We will also be using the parameter B_0 to denote the optical bandwidth seen by the receiver. The optical bandwidth of the receiver itself is very large, but the value of B_0 is usually determined by filters placed in the optical path between the transmitter and receiver.

By convention, we will measure B_e in baseband units and B_0 in passband units. Therefore, the minimum possible value of $B_0 = 2\, B_e$, to prevent signal distortion. The photon arrivals are accurately modeled by a Poisson random process. The photocurrent can be modeled as a stream of electronic charge impulses, each generated whenever a photon arrives at the photodetector. For signal powers that are usually encountered in optical communication systems, the photocurrent can be modeled as $I = \bar{I} + i_s$, where $\bar{I}$ is a constant current and i_s is a Gaussian random process with mean zero and autocorrelation $\sigma^2_{shot}\, \delta(\tau)$. For *pin* diodes, $\sigma^2_{shot} = 2e\bar{I}$. The constant current $\bar{I} = RP$, where R is the responsivity of the photodetector and P is the optical power. Here, we are assuming that the dark current, which is the photocurrent that is present in the absence of an input optical signal, is negligible. Thus, the shot noise current is also white and in a bandwidth B_e has the variance

$$\sigma^2_{shot} = 2e\bar{I}B_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

If we denote the load resistor of the photodetector by R_L , the total current in this resistor can be written as $I = \bar{I} + i_s + i_t$,

where i_t has the variance $\sigma^2_{thermal} = (4k_BT / R_L)B_e$. The shot noise and thermal noise currents are assumed to be independent so that, if B_e is the bandwidth of the receiver, this current can be modeled as a Gaussian random process with mean $\bar{I}$ and variance

$$\sigma^2 = \sigma^2_{shot} + \sigma^2_{thermal} \; . \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

Note that both the shot noise and thermal noise variances are proportional to the bandwidth B_e of the receiver. Thus, there is a trade-off between the bandwidth of a receiver and its noise performance. A receiver is usually designed so as to have just sufficient bandwidth to accommodate the desired bit rate so that its noise performance is optimized. In most practical direct detection receivers, the variance of the thermal noise component is much larger than the variance of the shot noise and determines the performance of the receiver.

Now, we will calculate the BER of a practical direct detection receiver. The receiver makes decisions as to which bit (0 or 1) was transmitted in each bit interval by sampling the photocurrent. Because of the presence of noise currents, the receiver could make a wrong decision resulting in an erroneous bit. In order to compute this bit error rate, we must understand the process by which the receiver makes a decision regarding the transmitted bit.

Consider a *pin* receiver. For a transmitted 1 bit, let the received optical power $P = P_1$ and let the mean photocurrent $\bar{I} = I_1$.

Then $I_1 = RP_1$ and the variance of the photocurrent is

$$\sigma^2_1 = 2eI_1B_e + 4k_BTB_e / R_L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

If P_0 and I_0 are the corresponding quantities for a 0 bit, $I_0 = RP_0$ and the variance of the photocurrent is

$$\sigma^2_0 = 2eI_0B_e + 4k_BTB_e / R_L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

For ideal on-off-keying (OOK), P_0 and I_0 are zero, but this is not always the case in practice.

Let I_1 and I_0 denote the photocurrent sampled by the receiver during a 1 bit and a 0 bit, respectively, and let a σ^2_1 and σ^2_0 represent the corresponding noise variances. The noise signals are assumed to be Gaussian. The actual variances will depend on the type of receiver. So, the bit decision problem faced by the receiver has the following mathematical formulation. The photocurrent for a 1 bit is a sample of a Gaussian random variable with mean I_1 and variance σ_1 (and similarly for the 0 bit as well). The receiver must look at this sample and decide whether the transmitted bit is a 0 or a 1. The possible probability density functions of the sampled photocurrent are sketched in Figure 3.2

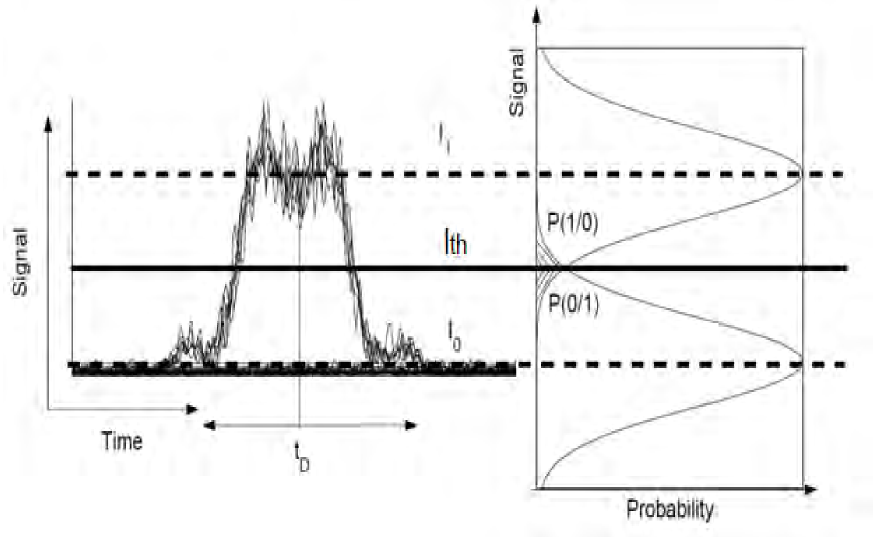


Figure -3.2: Probability density functions for the observed photocurrent.

There are many possible *decision rules* that the receiver can use; the receiver's objective is to choose the one that minimizes the bit error rate. This *optimum decision rule* can be shown to be the one that, given the observed photocurrent *I*, chooses the bit (0 or 1) that was *most likely* to have been transmitted. Furthermore, this optimum decision rule can be implemented as follows. Compare the observed photocurrent to a decision threshold I_{th} . If $I \geq I_{th}$, decide that a 1 bit was transmitted; otherwise, decide that a 0 bit was transmitted.

For the case when 1 and 0 bits are equally likely (which is the only case we consider in this thesis), the threshold photocurrent is given approximately by

$$I_{th} = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1} \quad \text{……………………………….. (3.8)}$$

This value is very close but not exactly equal to the optimal value of the threshold. The probability of error when a 1 was transmitted is the probability that $I < I_{th}$ and is denoted by $P[0|1]$. Likewise, $P[1|0]$ is the probability of deciding that a 1 was transmitted when actually a 0 was transmitted and is the probability that $I \geq I_{th}$. Both probabilities are indicated in Figure 3.2.

Let *Q(x)* denote the probability that a zero mean, unit variance Gaussian random variable exceeds the value *x*. Thus

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-y^2/2} dy \qquad (3.9)$$

It now follows that

$$P[0 \mid 1] = Q\left(\frac{I_1 - I_{th}}{\sigma_1}\right) \text{ and } P[1 \mid 0] = Q\left(\frac{I_{th} - I_0}{\sigma_0}\right)$$

Using (3.8), the BER is given by

$$BER = Q\left(\frac{I_1 - I_0}{\sigma_0 + \sigma_1}\right) \qquad (3.10)$$

The Q function can be numerically evaluated. Let $\gamma = Q^{-1}$ (BER). For a BER rate of 10^{-12}, we need $\gamma \approx 7$. For a BER rate of 10^{-9}, $\gamma \approx 6$.

It is particularly important to have a variable threshold setting in receivers if they must operate in systems with signal-dependent noise, such as optical amplifier noise. Many high-speed receivers do incorporate such a feature. However, many of the simpler receivers do not have a variable threshold adjustment and set their threshold corresponding to the average received current level, namely, $(I_1 + I_0)/2$. This threshold setting yields a higher bit error rate given by-

$$BER = \frac{1}{2}\left[Q\left(\frac{I_1 - I_0}{2\sigma_1}\right) + Q\left(\frac{I_1 - I_0}{2\sigma_0}\right)\right] \qquad (3.11)$$

(3.10) used to evaluate the BER when the received signal powers for a 0 bit and a 1 bit and the noise statistics are known.

3.2.4.4 Power Penalty

Power penalty is the extra power required to account for degradations due to different impairments that are present in the system. Usually each impairment results in a *power penalty* to the system. In the presence of an impairment, a higher signal power will be required at the receiver in order to maintain a desired bit error rate. One way to define the power penalty is as the increase in signal power required (in dB) to maintain the same bit error rate in the presence of impairments. Another way to define the power penalty is as the reduction in signal-to-noise ratio as quantified by the value of γ (the argument to the Q(.) function) due to a specific impairment. Here, we have used the latter definition since it is easier to calculate and consistent with popular usage.

Let P_1 denote the optical power received during a 1 bit and P_0 the power received during a 0 bit without any system impairments. The corresponding electrical currents are given by RP_1 and RP_0 respectively, where R is the responsivity of the photodetector.

Let σ_1 and σ_0 denote the noise standard deviations during a 1 bit and a 0 bit respectively. We also assume that the noise is Gaussian. Assuming equally likely ls and 0s, the bit error rate is obtained from (3.10) as

$$BER = Q\left(\frac{\Re(P_1 - P_0)}{\sigma_0 + \sigma_1}\right) \quad \text{………………………………..} \ (3.12)$$

In the presence of impairments, let $P_1', P_0', \sigma_1', \sigma_0'$ denote the received powers and noise standard deviations, respectively. Assuming an optimized threshold setting, the power penalty is given by [20].

$$PP = -10 \log\left(\frac{\dfrac{\Re(P_1' - P_0')}{\sigma_1' + \sigma_0'}}{\dfrac{\Re(P_1 - P_0)}{\sigma_1 + \sigma_0}}\right) \quad \text{………………………………..} \ (3.13)$$

The case of interest is when the dominant noise component is receiver thermal noise, for which $\sigma_0 = \sigma_1 = \sigma_{th}$. This is usually the case in unamplified direct detection *pin* receivers. In this case, or in any situation where the noise is independent of the signal power, the power penalty is given by

$$PP = -10 \log\left(\frac{(P_1' - P_0')}{(P_1 - P_0)}\right) \quad \text{………………………………..} \ (3.14)$$

3.2.4.5 Relative Intensity Noise (RIN)

Relative intensity noise (RIN) is the noise of the optical intensity (or actually power), normalized to its average value. In the context of intensity noise (optical power fluctuations) of a laser, it is common to specify the *relative intensity noise* (RIN), which is the power noise normalized to the average power level. The optical power of the laser can be considered to be

$$P(t) = \overline{P} + \delta P(t) \quad \text{………………………………..} \ (3.15)$$

with an average value and a fluctuating quantity δP with zero mean value. The relative intensity noise is then that of δP divided by the average power.

Relative intensity noise can be generated from cavity vibration, fluctuations in the laser gain medium or simply from transferred intensity noise from a pump source.

RIN is the signal-dependent noise. The optical feedback from multiple reflections along the fiber path can increase the effect of RIN.

3.3 Classification of Crosstalk

Crosstalk is the general term given to the effect of other signals on the desired signal. Almost every component in a WDM system introduces crosstalk of some form or another. The components include filters, wavelength multiplexers/demultiplexers, switches, semiconductor optical amplifiers and the fiber itself (by way of nonlinearities). Two forms of crosstalk arise in WDM systems: *interchannel crosstalk* and *intrachannel crosstalk.* The first case is when the crosstalk signal is at a wavelength sufficiently different from the desired signal's wavelength. This form of crosstalk is called interchannel crosstalk. Interchannel crosstalk can also occur through more indirect interactions. The second case is when the crosstalk signal is at the same wavelength as that of the desired signal. This form of crosstalk is called intrachannel crosstalk or also called homodyne crosstalk. Intrachannel crosstalk effects can be much more severe than interchannel crosstalk. In both cases, crosstalk results in a power penalty.

3.3.1 Intrachannel Crosstalk

Intrachannel crosstalk arises in transmission links due to reflections. This is usually not a major problem in point to point links since these reflections can be controlled. However, intrachannel crosstalk can be a major problem in networks. One source of this arises from cascading a wavelength demultiplexer (DEMUX) with a wavelength multiplexer (MUX) as shown in Figure 3.3.

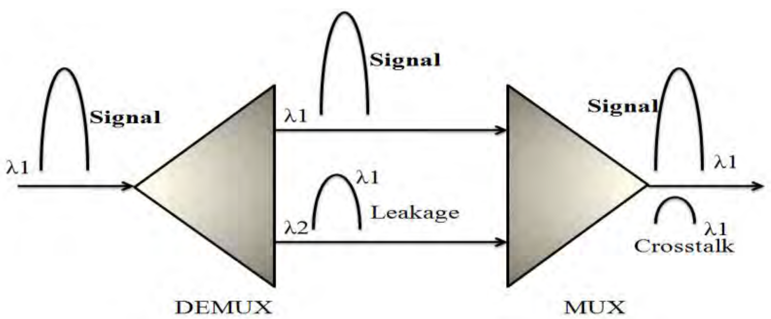


Figure- 3.3: Sources of intrachannel crosstalk. A cascaded wavelength demultiplexer and a multiplexer.

The DEMUX ideally separates the incoming wavelengths to different output fibers. In reality a portion of the signal at one wavelength say λ_i leaks into the adjacent channel λ_{i+1} because of nonideal suppression within the DEMUX. When the wavelengths are combined again into a single fiber by the MUX, a small portion of the λ_i that leaked into the λ_{i+1} channel will also leak back into the common fiber at the output. Although both signals contain the same data, they are not in phase with each other, due to different delays encountered by them. This causes intrachannel crosstalk. Intrachannel or homodyne crosstalk can be incoherent and coherent. Incoherent crosstalk occurs when the signal and interferer are from different optical sources. Coherent crosstalk occurs when the signal and interferer are from the same sources. The power penalty due to intrachannel crosstalk can be determined as follows.

Let P denote the average received signal power and εP the average received crosstalk power from a single other crosstalk channel. Assume that the signal and crosstalk are at the same optical wavelength. The electric field at the receiver can be written as

$$E(t) = \sqrt{2P}\, d_s(t)\cos[2\pi f_c t + \phi_s(t)] + \sqrt{2\varepsilon P}\, d_x(t)\cos[2\pi f_c t + \phi_x(t)] \quad \text{……………..} \; (3.16)$$

Here, $d_s(t)$={0,1}depending on whether a 0 or 1 is being sent in the desired channel, $d_s(t)$={0,1} depending on whether a 0 or 1 is being sent in the crosstalk channel, f_c is the frequency of the optical carrier and $\phi_s(t)$ *and* $\phi_x(t)$ are the random phases of the signal and crosstalk channels respectively. It is assumed that all channels have an ideal extinction ratio of ∞.

The photodetector produces a current that is proportional to the received power within its receiver bandwidth. This received power is given by

$$P_r = P d_s(t) + \varepsilon P d_x(t) + 2\sqrt{\varepsilon}\, P d_x(t)\cos[\phi_s(t) - \phi_x(t)] \quad \text{…………………..} \; (3.17)$$

Assuming ε << 1, we can neglect the ε term compared to the $\sqrt{\varepsilon}$ term. Also the worst case above is when the cos(.) = - 1. Using this, we get the received power during a 1 bit as

$$P_r(1) = P(1 - 2\sqrt{\varepsilon})$$

and the power during a 0 bit as

$$P_0(0) = 0$$

Therefore, using (3.13) power penalty can be written as

$$PP = -10\log(1 - 2\sqrt{\varepsilon}) \quad \text{……………….……….} \; (3.18)$$

3.3.2 Interchannel Crosstalk

Interchannel crosstalk can arise from a variety of sources. A simple example is an optical filter or demultiplexer that selects one channel and imperfectly rejects the others, as shown in Figure 3.4.

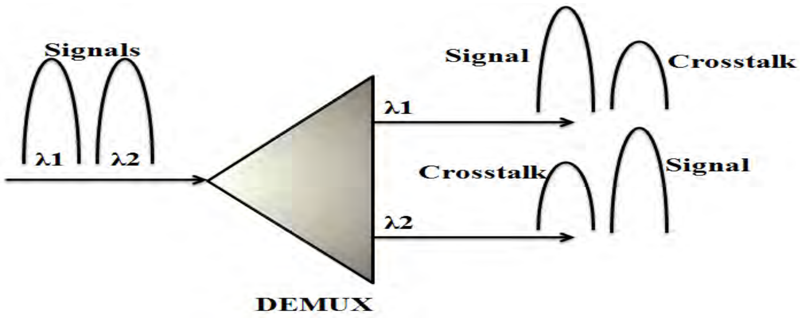


Figure -3.4: Sources of interchannel crosstalk. An optical demultiplexer (DEMUX).

Estimating the power penalty due to interchannel crosstalk is fairly straightforward. If the wavelength spacing between the desired signal and the crosstalk signal is large compared to the receiver bandwidth, (3.15) can be written as

$$P_r = Pd_s(t) + \varepsilon Pd_x(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.19)$$

Therefore, in the worst case, we have

$P_r(1) = P$ and $P_r(0) = \varepsilon P$

Using (3.13) power penalty can be written as

$$PP = -10\log(1-\varepsilon) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.20)$$

3.4 GPON Quad Play Proposed Structure using CWDM Technology

International Telecommunication Union sets Global Standard for Metro Networks Standard needed to satisfy the demands of voice, data and multimedia services for low-cost short-haul transport solutions in urban centres.

(i) The ITU has set a global standard for Metro ‘Optical Fiber’ Networks that will expand the use of Coarse Wavelength Division Multiplexing (CWDM) in metropolitan networks.

(ii) This standard is necessary to meet the increasing demand of voice, data and multimedia services for low-cost short-haul optical transport solutions.

(iii) Where the distances are shorter and the need for capacity is less, CWDM applications are able to use wider channel spacing and less expensive equipment, yet achieve the same quality standards of long-haul optical fiber systems.

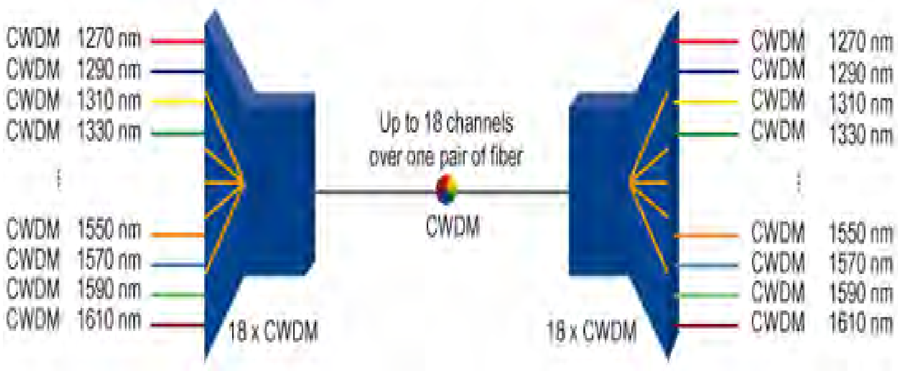


Figure-3.5: CWDM channel Spacing

Originally, the term "coarse wavelength division multiplexing" was fairly generic, and meant a number of different things. In general, these things shared the fact that the choice of channel spacings and frequency stability was such that erbium doped fiber amplifiers (EDFAs) could not be utilized. Prior to the relatively recent ITU standardization of the term, one common meaning for coarse WDM meant two (or possibly more) signals multiplexed onto a single fiber, where one signal was in the 1550 nm band, and the other in the 1310 nm band.

In 2002, the ITU standardized a channel spacing grid for use with CWDM (ITU-T G.694.2), using the wavelengths from 1270 nm through 1610 nm with a channel spacing of 20 nm. (G.694.2 was revised in 2003 to shift the actual channel centers by 1, so that strictly speaking the center wavelengths are 1271 to 1611 nm. [2]) Many CWDM wavelengths below 1470 nm are considered "unusable" on older G.652 specification fibers, due to the increased attenuation in the 1270-1470 nm bands. Newer fibers which conform to the G.652.C and G.652.D standards, such as Corning SMF-28e and Samsung Widepass nearly eliminate the "water peak" attenuation peak and allow for full operation of all 20 ITU CWDM channels in metropolitan networks.

The Ethernet LX-4 10 Gbit/s physical layer standard is an example of a CWDM system in which four wavelengths near 1310 nm, each carrying a 3.125 gigabit-per-second (Gbit/s) data stream, are used to carry 10 Gbit/s of aggregate data.

The main characteristic of the recent ITU CWDM standard is that the signals are not spaced appropriately for amplification by EDFAs. This, therefore, limits the total CWDM optical span to somewhere near 60 km for a 2.5 Gbit/s signal, which is suitable for use in metropolitan applications. The relaxed optical frequency stabilization requirements allow the associated costs of CWDM to approach those of non-WDM optical components.

CWDM is also being used in cable television networks, where different wavelengths are used for the downstream and upstream signals. In these systems, the wavelengths used are often widely separated, for example the downstream signal might be at 1310 nm while the upstream signal is at 1550 nm.

An interesting and relatively recent development relating coarse WDM is the creation of small form factor pluggable (SFP) transceivers utilizing standardized CWDM wavelengths. GBIC and SFP optics allow for something very close to a seamless upgrade in even legacy systems that support SFP interfaces. Thus, a legacy switch system can be easily "converted" to allow wavelength multiplexed transport over a fiber simply by judicious choice of transceiver wavelengths, combined with an inexpensive passive optical multiplexing device.

Passive CWDM is an implementation of CWDM that uses no electrical power. It separates the wavelengths using passive optical components such as bandpass filters and prisms. Many manufacturers are promoting passive CWDM to deploy fiber to the home.

A WDM-PON designer must decide on the appropriate wavelengths and their spacing, based on which the selection of devices may differ significantly. The two major wavelength options—coarse WDM (CWDM) PON and dense WDM (DWDM) PON. The OLT and ONUs have optical transmitters, receivers, multiplexers, and demultiplexers. Several WDM-PON transmitter options have been proposed. Receiver options, which are dependent on both loss and protocols, various multiplexers and demultiplexers to be deployed at remote nodes (RNs). Wavelength Options Wavelength spacing of more than 20 nm is generally called coarse WDM (CWDM). Optical interfaces, which have been standardized for CWDM, can be found in ITU G.695, while the spectral grid for CWDM is defined in ITU G.694.2. If the complete wavelength range of 1271 nm to 1611 nm, as defined in ITU G.694.2, is used with 20 nm spacing, then a total 18 CWDM channels are available. A low-water-peak fiber defined in ITU G.652 C & D, which eliminates power attenuation in the 1370–1410 nm range seen in a normal single-mode fiber, can be used for this wide spectrum of transmission. The dispersion parameter indicates signal broadening, and this factor may limit the transmission distance as the data rate becomes higher.

Since strict tuning of wavelengths is not needed for the CWDM-PON, a thermal control part, called a thermo- electric cooler (TEC), is not required, making it cheaper than the DWDM-PON. Furthermore, the wavelength multiplexer with low channel crosstalk can be implemented easily for CWDM. It has been argued that the total system cost is 40% cheaper for the CWDM-PON. The primary disadvantage of CWDM is that the number of channels is limited; therefore, the CWDM-PON lacks in scalability, especially when a normal single-mode fiber with water-peak attenuation range is used. Another disadvantage is that the shorter wavelength channels experience higher loss, thereby limiting the transmission distance or splitting ratio. A brief example of the CWDM-PON can be found in the so-called “triple-play” PON service, where the 1550 nm wavelength channel is used for optional video CATV, the 1490 nm wavelength channel is used for downstream voice and data, while the 131 nm wavelength channel is used for upstream transmission. An expanded application adopts 1360–1480 nm CWDM channels for premium business services, while usual triple-play services are provided to normal subscribers. DWDM has wavelength spacing that is far lesser than that of CWDM, typically less than 3.2 nm, because DWDM has been developed to transmit many wavelengths in a limited spectrum region where an EDFA can be used. A DWDM-PON is expected to be very useful for providing enough bandwidth to many subscribers, and it is regarded as the ultimate PON system. ITU G.692 defines a laser grid for point-to-point WDM systems based on 100 GHz wavelength spacing with a centre wavelength of 193.1 THz (1553.52 nm) over the frequency region of 196.1 THz (1528.77 nm) to 191.7 THz (1563.86 nm). This 100 GHz spacing has been applied to many DWDM systems. But, 50 GHz spaced laser diodes (LDs) and filters are commercially available today, and they can be used to increase the number of channels. Also, wavelengths reaching up to 1600 nm have been used to exploit the cyclic property of the AWG, by having just one AWG at a remote node for demultiplexing and multiplexing in downstream and upstream directions, respectively. In a DWDM-PON, the wavelength of each optical source and the center wavelength of the WDM filter should be monitored and controlled carefully to avoid crosstalk between adjacent channels. Therefore, the DWDM PON costs more than the CWDM-PON in field deployment since it needs wavelength-tuned devices and temperature control.

Coarse wavelength division multiplexing (CWDM) is set to introduce multi wavelength optical systems cheaply into the metro network. Compared to DWDM, CWDM achieves cost reduction via the use of cheaper wide channel spacing filters, which in turn allow the use of cheaper uncooled lasers in CWDM systems. However, because CWDM systems are non-amplified, the attainable system.

CWDM network design approach that can be employed to maximize the perimeter of a 16-channel CWDM transmission network based on a G.652D-class fiber [zero water peak fiber (ZWPF)], such as All Wave.

All 16 channels of the full spectrum (FS) CWDM channel plan extending from 1310* nm in the O-band to 1610 nm in the L-band can be supported on a single fiber, A wavelength assignment algorithm assigns wavelength bands to the nodes in such a way that the accumulated filter losses incurred by the O-band wavelengths around the ring are minimized and increase to its maximum in the L-band. In contrast, ZWPF attenuation as a function of wavelength reaches a maximum in the O-band and monotonically decreases to a minimum value in the L-band. Hence, the increasing attenuation slope of the filters toward longer wavelengths is partially offset by a falling attenuation slope of the fiber loss curve.

Therefore, the main purpose of this approach is to increase the application range of nonamplified CWDM for metro rings, to demonstrate the competitiveness of CWDM for new segments of the metro market that are dominated by short-reach DWDM, time division multiplexing (TDM), and space division multiplexing (SDM) for metro deployment. This will further enhance the competitiveness of G.652D fiber since these fibers offer a seamless support of all 16 CWDM channels on a single fiber compared to standard G.652 (SSMF), which only supports a maximum of 12 CWDM channels. The FS-CWDM channel plan being standardized by the ITU-T comprises 16 non-amplified channels, with center wavelengths starting at 1310 nm with 20-nm channel spacing is shown in Table-3.1

Table-3.1: IUT-Based CWDM Channel Plan for 16 CWDM Channels

SN	Fiber att.[B/km]	Laser Wavelength (nm)	Channel#	Band
1	0.36	1310	1	O- Band
2	0.335	1330	2	
3	0.322	1350	3	E-Band
4	0.311	1370	4	
5	0.333	1390	5	

6	0.291	1410	6	
7	0.281	1430	7	S-, C-, L-band
8	0.272	1450	8	
9	0.266	1470	9	
10	0.260	1490	10	
11	0.254	1510	11	
12	0.252	1530	12	
13	0.250	1550	13	
14	0.250	1570	14	
15	0.257	1590	15	
16	0.266	1610	16	

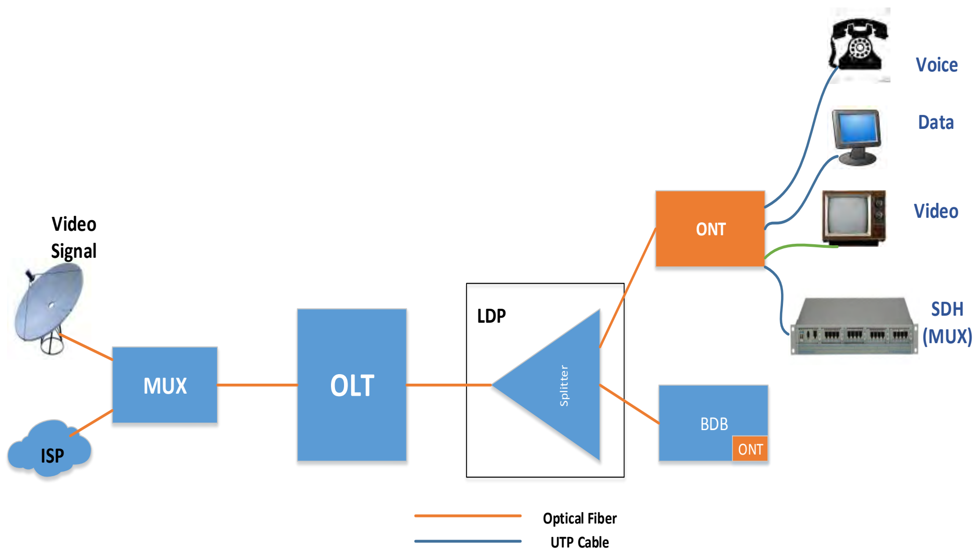


Figure-3.6: Proposed quad play architecture

The proposed quad play structure is not like traditional tripe play architecture. The Video signal and the ISP's connection will combinely enter into a MUX and the modulated signal will enter into OLT. The OLT will propagate the modulated signal towards the ONTs. And as usual from the ONT's ethernet port, the user will receive the signals. In traditional triple play, OLT did the modulation and OLT becomes busier and its uses was high, but in Quad play architecture the modulation was done in MUX, for that the OLT does not spent time for modulation.

3.4.1 Synchronous Digital Hierarchy (SDH)

Synchronous Optical Networking (SONET) and Synchronous Digital Hierarchy (SDH) are standardized protocols that transfer multiple digital bit streams synchronously over optical fiber using lasers or highly coherent light from light-emitting diodes (LEDs). At low transmission rates, data can also be transferred via an electrical interface. The method was developed to replace the plesiochronous digital hierarchy (PDH) system for transporting large amounts of telephone calls and data traffic over the same fiber without synchronization problems.

In digital telephone transmission, "synchronous" means the bits from one call are carried within one transmission frame. "Plesiochronous" means "almost (but not) synchronous," or a call that must be extracted from more than one transmission frame.

SDH uses the following Synchronous Transport Modules (STM) and rates: STM-1 (155 megabits per second), STM-4 (622 Mbps), STM-16 (2.5 gigabits per second), and STM-64 (10 Gbps).

Today's carrier backbone networks are supported by synchronous optical network (SONET) and synchronous digital hierarchy (SDH) transmission technologies. SONET is the standard used in the United States and SDH is the standard used outside the United States.

SONET/SDH specification outlines the frame format, multiplexing method, and synchronization method between the equipment, as well as the specifying optical interface.

SONET/SDH will continue to play a key role in the next generation of networks for many carriers. In the core network, the carriers offer services such as telephone, dedicated leased lines, and Internet protocol (IP) data, which are continuously transmitted.

3.4.1.1 Advantages of SDH Network

3.4.1.1.1 Synchronous Digital Transmission

Until the introduction of SONET in the mid-1980s, plesiochronous digital hierarchy (PDH) systems commonly used data multiplexing technology. The primary problem with PDH was that to extract low-speed traffic, all traffic that was multiplexed to higher speeds had to be de-multiplexed into lower speeds. With PDH, the equipment had to support multiplexing and de-multiplexing the signal, adding cost and complexity to the network.

SONET was introduced as a synchronous transmission system that could directly extract low-speed signals from multiplexed high-speed traffic. Based on the ANSI standard, the CCITT approved the international standard known as SDH based on the SONET technology.

3.4.1.1.2 Mid-Span Meet

The adoption and acceptance of SONET allowed carriers to be able to choose equipment from different vendors instead of using only a single vendor with a proprietary optical format. The ability to mix equipment from different vendors in one system is called the "Mid-Span Meet".

3.4.1.1.3 Speed

SONET and SDH give carriers much more bandwidth to carry voice and data traffic than PDH technology. The base rate for SONET is 51 Mbps. Synchronous transport signal (STS-n) refers to the SONET signal in the electrical domain, and optical carrier (OC-n) refers to the SONET signal in the optical domain. The base rate for SDH is 155 Mbps. Synchronous transport module (STM-n) refers to the SDH signal level in both the electrical and optical domains. See Table 3.2.

Table 3.2: Synchronous Transport Signal (STS) & Synchronous Transport Module (STM)

SONET	SONET	SDH	Both
North America STS Level	**North America OC Level**	**European STM Level**	**Line Rates (Mbps)**
STS-1	OC-1	N/A	51.84
STS-3	OC-3	STM-1	155.52
STS-12	OC-12	STM-4	622.08
STS-48	OC-48	STM-16	2,488.32
STS-192	OC-192	STM-64	9,953.28
STS-768	OC-768	STM-256	39,813.12

3.4.1.1.4 Reliability

Carriers require an extremely reliable network and cannot afford downtime. Therefore, most SONET/SDH networks have a ring structure, which adds high reliability to the overall transmission network. Even if the optical fiber is cut, the transmission path is backed-up and restored within 50 ms.

A SONET/SDH transmission network is composed of several pieces of equipment, including:

1. Terminal multiplexer (TM)
2. Add-drop multiplexer (ADM)
3. Repeater
4. Digital cross-connect system (DCS)

3.5 Various Parameter Calculation of CWDM Technology

Crosstalk effect of CWDM technology calculated and some example link also discussed in this section.

3.5.1 Fiber Loss and Filter Loss Calculation:

Summarizing the impact of loss originating from various sources. First, there is the spectrally dependent loss of the optical transmission fiber and the different channels of the CWDM multiplexer with a significant variation between the CWDM channels due to the wide transmission bandwidth of 300 nm. Secondly, there are other sources of loss such as connector loss that are generally independent of wavelengths or particular channel numbers.

3.5.1.1 Fiber loss W(λ_i , k):

$W(\lambda_i, k) = P - S - F(\lambda_i, k) - C(\lambda_i, k)$

Here,

P=Source Power

S=receiver sensitivity

$F(\lambda_i, k)$ = filter insertion loss incurred by wavelength assigned to ONT_k

$C(\lambda_i, k)$= connector loss incurred by wavelength assigned to ONT_k

3.5.1.2 Filter loss F(λ_i , k):

<u>Case-1:</u>

ONT_k -to-OLT path is the higher-loss-path:

The path ONT_k -to-OLT, the filter loss F(λi, k) incurred by a wavelength λ_i is calculated as follows:

$F(\lambda_i, k) = f_{mux} + f_{add} + (n - k) + f_{exp} + f_{drop} + f_{demux}$ if n+1> 2k

where

f_{mux}= mux loss at ONT Nk

f_{add} = add loss at ONT Nk

f_{exp} = express losses at nodes Nk +1 to Nn

f_{drop} = drop loss at the Splitter

f_{demux} = demux loss at the ONT.

<u>Case-2:</u>

OLT-to-ONT_k path is the higher loss path:

On the path from the OLT-to-ONT_k, the filter loss incurred by a wave¬length , is:

$F(\lambda_i, k) = f_{mux} + f_{add} + (k-1) f_{exp} + f_{drop} + f_{demux}$ if 2k>n+1

where

f_{mux}= mux loss at the OLT

f_{add} = add loss at the OLT

f_{exp} = express losses at ONTs N_1 to N_{k-1}

f_{drop} = drop loss at the Splitter

f_{demux} = demux loss at the ONT.

Therefore, combining Equations, the filter loss incurred by a wavelength, assigned to ONT_k is given by:

$$F(\lambda_i, k) = \begin{Bmatrix} f_{mux} + f_{add} + (n-k) f_{exp} + f_{drop} + f_{demux} \;.......... \;....... \; if \;..n+1>2k \\ f_{mux} + f_{add} + (k-1) f_{exp} + f_{drop} + f_{demux} \;.......... \;........ \; if \;...2k \geq n+1 \end{Bmatrix} \quad .... (3.23)$$

c) Connector loss C(λ_i, k):

Following the same procedure as for the filter loss derivations, the connector loss incurred by a wavelength λ_i assigned to ONT_k is given by:

$$c(\lambda_i, k) = \begin{Bmatrix} (n+1-k) C_{sp} \;.......... \;..if \;..... \; n+1>2k \\ KC_{sp} \;.......... \;.......... \;.......... \;..if \;...... \; 2k \geq n+1 \end{Bmatrix} \quad ....(3.24)$$

where Csp is the connector loss per span, which is the same for each node and independent of wavelength. So for the estimated loss of a cable plant, calculate the approximate loss as:

Path loss (Source to Destination) = (0.5 dB X # connectors) + (0.2 dB X# splices) + (fiber attenuation X the total length of cable).

3.6 Summary

The basic discussion between DWDM and CWDM has been discussed and a proposed quad play architecture using CWDM technology has been discussed. GPON quad play architecture is based on using MUX instead of using EDFA. Direct modulated laser also used.

Chapter 4

Analytical Analysis

Crosstalk effect, power penalty, relative intensity noise and bit error rate are the main component to be analysed. Using loss path calculation. Formula, a sample sensitivity calculation sheet has been prepared and found that 1550 nm wavelength response with minimum dB loss and it shows better performance.

4.1 Introduction

Performance of the optical add-drop multiplexers is evaluated in the following sections. The analysis is carried out in terms of BER, power penalty and relative intensity noise, the results are obtained at specific range of wavelength, varying number of channels and input power. The parameter values used in the theoretical computations are given in Table 4.1.

Table- 4.1 Parameter values use for theoretical calculations

Parameter (unit)	Parameter value
Temperature, T (^{0}F)	300
Boltzmann's constant, k_B (J/^{0}K)	1.38×10^{-23}
Responsivity of photodetector, *R*	0.8
wavelength, λ_{best}(nm)	1310-1610
Grating length, *l* (m)	0.05
New, η	0.80
refractive-index perturbation, Δn	1.55×10^{-4}
Resistance, R_L(ohm)	50
Bandwidth B_o (Hz)	2.5×10^{9}
Input power, *P*(mw)	varied
Number of channel, *n*	1-60
Optical wavelength, λ(nm)	1548-1551

4.2 Effect of Power Penalty and Relative Intensity Noise

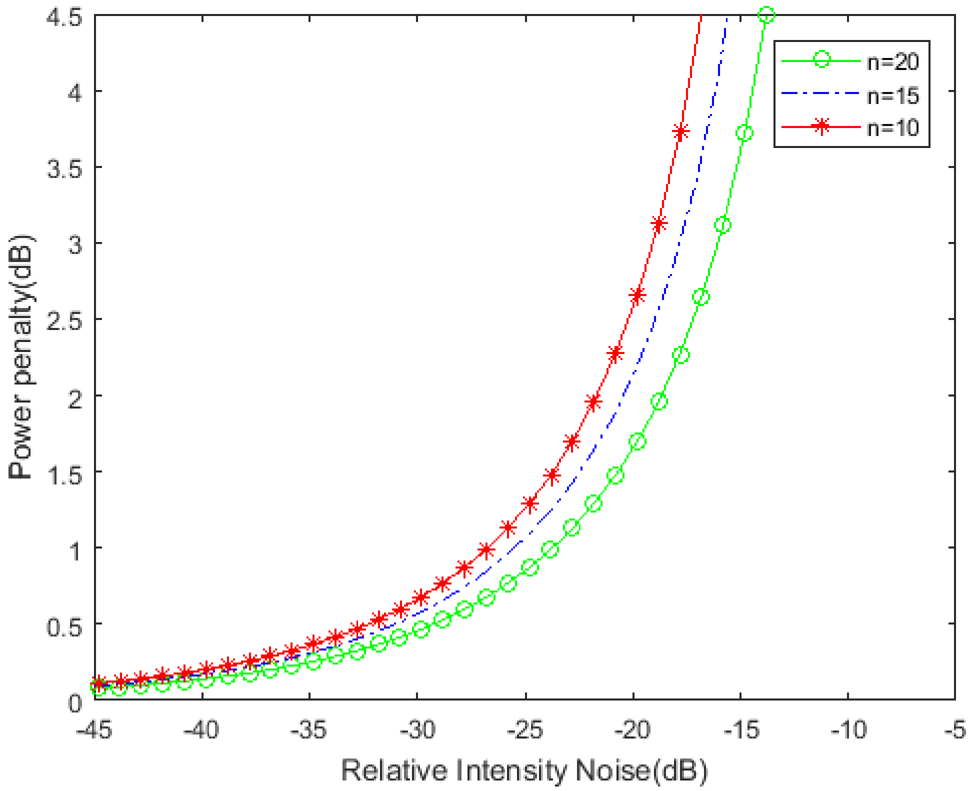


Figure-4.1: Power penalty Vs RIN

Figure 4.1 shows the plots of power penalty vs relative intensity noise for different crosstalk power and various interfering signals. It is observed that the power penalty is increased with increasing the number of interfering channels for a fixed RIN level. For example, the amount of power penalty is 1.6dB at n=10, 2.01dB at n=15 and 2.51dB at n=20 for the RIN of -20dB. Here, n is the number of interfering signals.

4.3 Effect of Power Penalty and Crosstalk

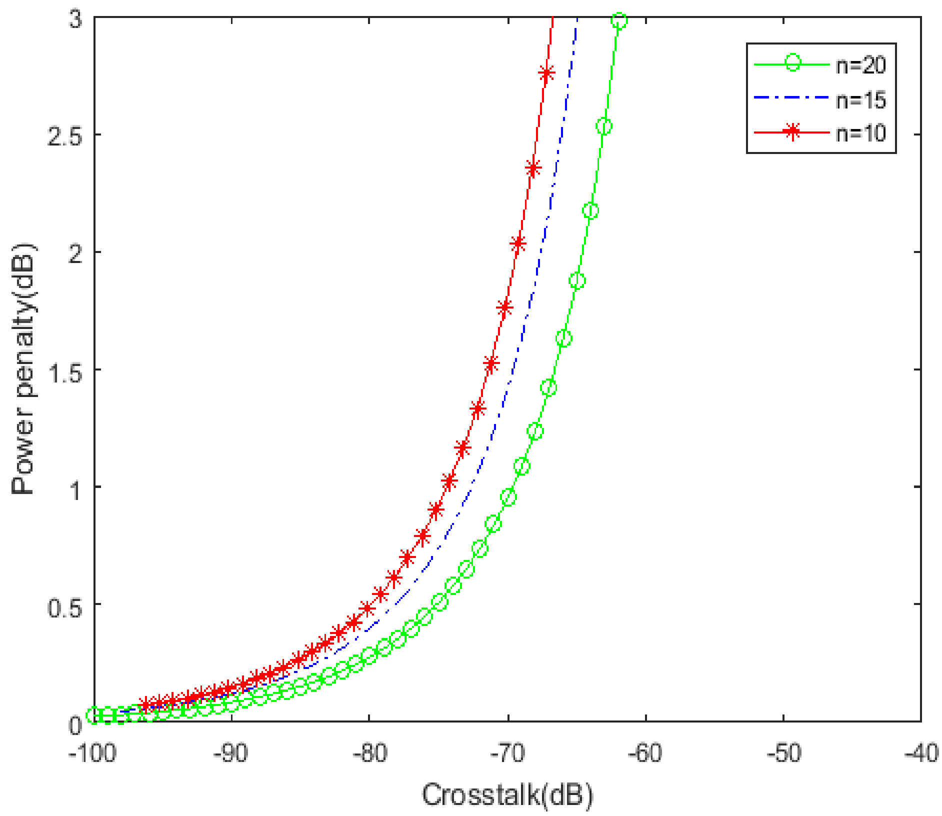


Figure-4.2: Power penalty Vs Crosstalk

Figure 4.2 shows the plots of power penalty versus crosstalk for different values of channel (n). It is noticed that for a fixed crosstalk power, the power penalty is increased with increasing the number of channel. For instance, the required power penalty is 1.25dB at n=10, 1.58dB at n=15 and 1.95dB at n=20 for the crosstalk power of -70dB.

4.4 Effect of Bit Error Rate and Received Power

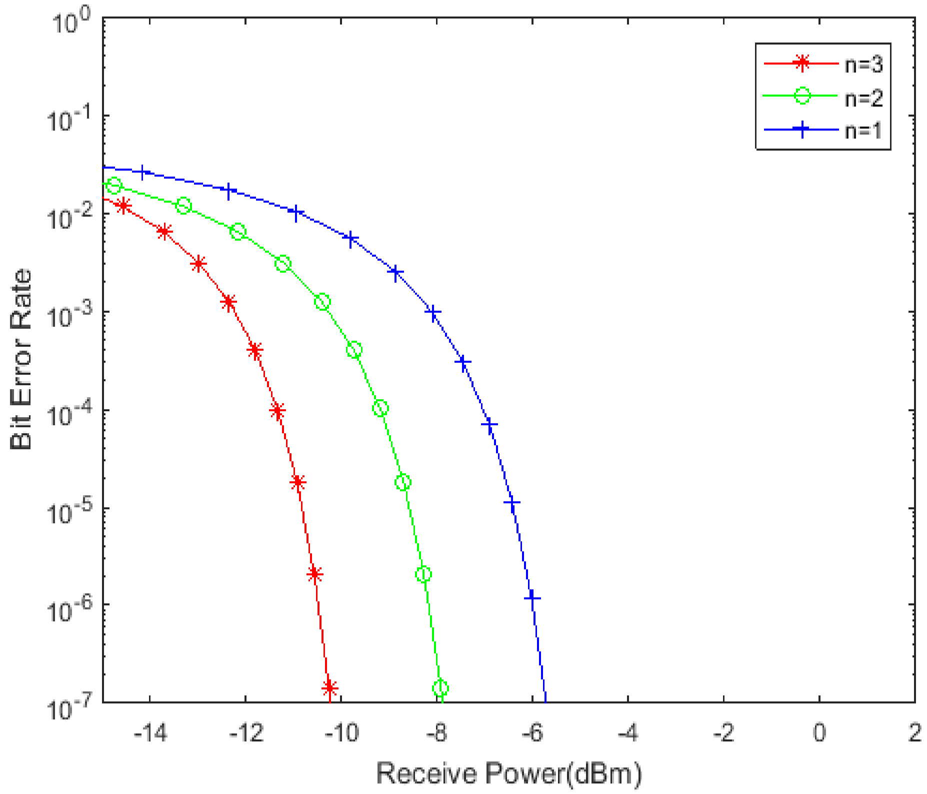


Figure-4.3: Bit Error Rate Vs Receive Power

Figure 4.3 shows the variation of BER and received power for different values of n. Keeping the constant BER, the received power is varied with n. For example, the received power is -10.3dB at n=3, -7.9 dB at n=2 and -5.8 dB at n=1 for BER of 10^{-2}. So, for three interfering signals, amount of power penalty is about 2 dB.

4.5 Crosstalk in DWDM and CWDM

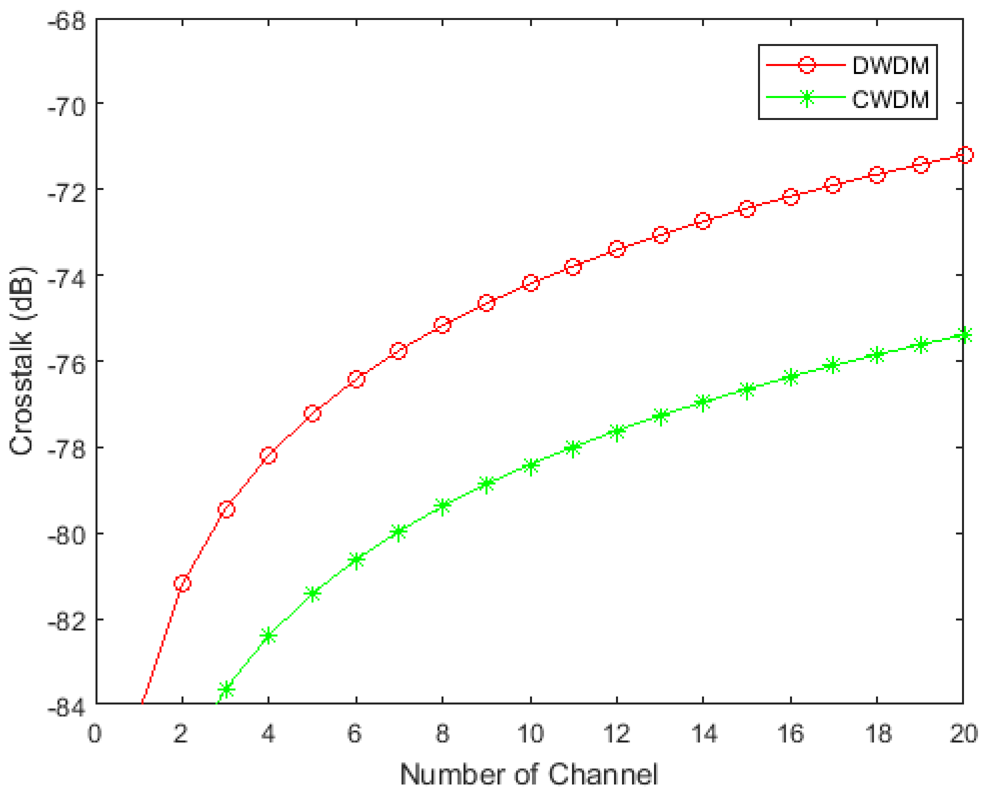


Figure-4.4: Crosstalk Vs Number of Channel

Figure 4.5 shows the crosstalk as a function of wavelengths. The wavelengths in the reflected band may be used to add or drop. The figure shows that in CWDM, when the number of channel is 14, crosstalk is -78 dB while in DWDM -74 dB.

4.6 Sample sensitivity Calculation sheet

Using the formula of section 3.5.1.1 and 3.5.1.2, sample sensitivity calculation sheet has been prepared.

Table-4.2: 1:8 Splitter with 10KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	3.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	26.48	
1330	0.335	3.35	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	26.205	
1350	0.322	3.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	26.062	
1370	0.311	3.11	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.941	
1390	0.333	3.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	26.183	
1410	0.291	2.91	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.721	
1430	0.281	2.81	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.611	
1450	0.272	2.72	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.512	
1470	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.446	
1490	0.26	2.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.38	
1510	0.254	2.54	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.314	
1530	0.252	2.52	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.292	
1550	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.27	Best
1570	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.271	
1590	0.257	2.57	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.347	
1610	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	25.446	

Using 1:8 Splitter with 10 KM distance, it is observed that the minimum sensitivity is -25.27 dB at 1550 nm wavelength and the highest sensitivity is -26.48 dB at 1310 nm wavelength.

Table-4.3: 1:8 Splitter with 20KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	7.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.08	
1330	0.335	6.7	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	29.555	
1350	0.322	6.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	29.282	
1370	0.311	6.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	29.051	
1390	0.333	6.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	29.513	
1410	0.291	5.82	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	28.631	
1430	0.281	5.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	28.421	
1450	0.272	5.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	28.232	
1470	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	28.106	
1490	0.26	5.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	27.98	
1510	0.254	5.08	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	27.854	
1530	0.252	5.04	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	27.812	
1550	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	27.77	Best
1570	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	27.771	
1590	0.257	5.14	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	27.917	
1610	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	28.106	

Using 1:8 Splitter with 20 KM distance, it is observed that the minimum sensitivity is -27.77 dB at 1550 nm wavelength and the highest sensitivity is -30.08 dB at 1310 nm wavelength.

Table-4.4: 1:8 Splitter with 30KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	10.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	33.68	
1330	0.335	10.05	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	32.905	
1350	0.322	9.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	32.502	
1370	0.311	9.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	32.161	
1390	0.333	9.99	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	32.843	
1410	0.291	8.73	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	31.541	
1430	0.281	8.43	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	31.231	
1450	0.272	8.16	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.952	
1470	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.766	
1490	0.26	7.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.58	
1510	0.254	7.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.394	
1530	0.252	7.56	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.332	
1550	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.27	Best
1570	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.271	
1590	0.257	7.71	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.487	
1610	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	10.72	0.3+0.3=0.6	0.3	30.766	

Using 1:8 Splitter with 30 KM distance, it is observed that the minimum sensitivity is -30.27 dB at 1550 nm wavelength and the highest sensitivity is -33.68 dB at 1310 nm wavelength.

Table-4.5: 1:16 Splitter with 10KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	3.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	29.71	
1330	0.335	3.35	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	29.435	
1350	0.322	3.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	29.292	
1370	0.311	3.11	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	29.171	
1390	0.333	3.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	29.413	
1410	0.291	2.91	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.951	
1430	0.281	2.81	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.841	
1450	0.272	2.72	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.742	
1470	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.676	
1490	0.26	2.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.61	
1510	0.254	2.54	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.544	
1530	0.252	2.52	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.522	
1550	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.5	Best
1570	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.51	
1590	0.257	2.57	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.577	
1610	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	28.676	

Using 1:16 Splitter with 10 KM distance, it is observed that the minimum sensitivity is -28.5 dB at 1550 nm wavelength and the highest sensitivity is -29.71 dB at 1310 nm wavelength.

Table-4.6: 1:16 Splitter with 20KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	7.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.31	
1330	0.335	6.7	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	32.785	
1350	0.322	6.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	32.512	
1370	0.311	6.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	32.281	
1390	0.333	6.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	32.743	
1410	0.291	5.82	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.861	
1430	0.281	5.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.651	
1450	0.272	5.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.462	
1470	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.336	
1490	0.26	5.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.21	
1510	0.254	5.08	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.084	
1530	0.252	5.04	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.042	
1550	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31	Best
1570	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.1	
1590	0.257	5.14	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.147	
1610	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	31.336	

Using 1:16 Splitter with 20 KM distance, it is observed that the minimum sensitivity is -31 dB at 1550 nm wavelength and the highest sensitivity is -33.31 dB at 1310 nm wavelength.

Table-4.7: 1:16 Splitter with 30KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	10.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	36.91	
1330	0.335	10.05	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	36.135	
1350	0.322	9.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	35.732	
1370	0.311	9.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	35.391	
1390	0.333	9.99	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	36.073	
1410	0.291	8.73	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	34.771	
1430	0.281	8.43	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	34.461	
1450	0.272	8.16	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	34.182	
1470	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.996	
1490	0.26	7.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.81	
1510	0.254	7.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.624	
1530	0.252	7.56	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.562	
1550	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.5	Best
1570	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.51	
1590	0.257	7.71	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.717	
1610	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	13.95	0.3+0.3=0.6	0.3	33.996	

Using 1:16 Splitter with 30 KM distance, it is observed that the minimum sensitivity is -33.5 dB at 1550 nm wavelength and the highest sensitivity is -36.91 dB at 1310 nm wavelength.

Table-4.8: 1:32 Splitter with 10KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	3.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	33.06	
1330	0.335	3.35	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.785	
1350	0.322	3.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.642	
1370	0.311	3.11	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.521	
1390	0.333	3.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.763	
1410	0.291	2.91	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.301	
1430	0.281	2.81	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.191	
1450	0.272	2.72	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.092	
1470	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.026	
1490	0.26	2.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	31.96	
1510	0.254	2.54	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	31.894	
1530	0.252	2.52	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	31.872	
1550	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	31.85	Best
1570	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	31.851	
1590	0.257	2.57	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	31.927	
1610	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	32.026	

Using 1:32 Splitter with 10 KM distance, it is observed that the minimum sensitivity is -31.85 dB at 1550 nm wavelength and the highest sensitivity is -33.06 dB at 1310 nm wavelength.

Table-4.9: 1:32 Splitter with 20KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	7.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	36.66	
1330	0.335	6.7	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	36.135	
1350	0.322	6.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	35.862	
1370	0.311	6.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	35.631	
1390	0.333	6.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	36.093	
1410	0.291	5.82	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	35.211	
1430	0.281	5.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	35.001	
1450	0.272	5.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.812	
1470	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.686	
1490	0.26	5.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.56	
1510	0.254	5.08	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.434	
1530	0.252	5.04	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.392	
1550	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.35	Best
1570	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.351	
1590	0.257	5.14	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.497	
1610	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	34.686	

Using 1:32 Splitter with 20 KM distance, it is observed that the minimum sensitivity is -34.35 dB at 1550 nm wavelength and the highest sensitivity is -36.66 dB at 1310 nm wavelength.

Table-4.10: 1:32 Splitter with 30KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	10.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	40.26	
1330	0.335	10.05	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	39.485	
1350	0.322	9.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	39.082	
1370	0.311	9.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	38.741	
1390	0.333	9.99	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	39.423	
1410	0.291	8.73	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	38.121	
1430	0.281	8.43	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	37.811	
1450	0.272	8.16	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	37.532	
1470	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	37.346	
1490	0.26	7.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	37.16	
1510	0.254	7.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	36.974	
1530	0.252	7.56	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	36.912	
1550	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	36.85	Best
1570	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	36.851	
1590	0.257	7.71	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	37.067	
1610	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	17.3	0.3+0.3=0.6	0.3	37.346	

Using 1:32 Splitter with 30 KM distance, it is observed that the minimum sensitivity is -36.85 dB at 1550 nm wavelength and the highest sensitivity is -40.26 dB at 1310 nm wavelength.

Table-4.11: 1:64 Splitter with 10KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	3.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	36.54	
1330	0.335	3.35	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	36.265	
1350	0.322	3.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	36.122	
1370	0.311	3.11	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	36.001	
1390	0.333	3.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	36.243	
1410	0.291	2.91	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.781	
1430	0.281	2.81	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.671	
1450	0.272	2.72	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.572	
1470	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.506	
1490	0.26	2.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.44	
1510	0.254	2.54	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.374	
1530	0.252	2.52	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.352	
1550	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.33	Best
1570	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.331	
1590	0.257	2.57	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.407	
1610	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	35.506	

Using 1:64 Splitter with 10 KM distance, it is observed that the minimum sensitivity is -35.33 dB at 1550 nm wavelength and the highest sensitivity is -36.54 dB at 1310 nm wavelength.

Table-4.12: 1:64 Splitter with 20KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	7.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.14	
1330	0.335	6.7	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	39.615	
1350	0.322	6.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	39.342	
1370	0.311	6.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	39.111	
1390	0.333	6.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	39.573	
1410	0.291	5.82	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	38.691	
1430	0.281	5.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	38.481	
1450	0.272	5.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	38.292	
1470	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	38.166	
1490	0.26	5.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	38.04	
1510	0.254	5.08	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	37.914	
1530	0.252	5.04	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	37.872	
1550	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	37.83	Best
1570	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	37.831	
1590	0.257	5.14	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	37.977	
1610	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	38.166	

Using 1:64 Splitter with 20 KM distance, it is observed that the minimum sensitivity is -37.83 dB at 1550 nm wavelength and the highest sensitivity is -40.14 dB at 1310 nm wavelength.

Table-4.13: 1:64 Splitter with 30KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	10.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	43.74	
1330	0.335	10.05	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	42.965	
1350	0.322	9.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	42.562	
1370	0.311	9.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	42.221	
1390	0.333	9.99	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	42.903	
1410	0.291	8.73	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	41.601	
1430	0.281	8.43	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	41.291	
1450	0.272	8.16	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	41.012	
1470	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.826	
1490	0.26	7.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.64	
1510	0.254	7.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.454	
1530	0.252	7.56	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.392	
1550	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.33	Best
1570	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.331	
1590	0.257	7.71	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.547	
1610	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	20.78	0.3+0.3=0.6	0.3	40.826	

Using 1:64 Splitter with 30 KM distance, it is observed that the minimum sensitivity is -40.33 dB at 1550 nm wavelength and the highest sensitivity is -43.74 dB at 1310 nm wavelength.

Table-4.14: 1:128 Splitter with 10KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	3.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	39.95	
1330	0.335	3.35	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	39.675	
1350	0.322	3.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	39.532	
1370	0.311	3.11	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	39.411	
1390	0.333	3.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	39.653	
1410	0.291	2.91	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	39.191	
1430	0.281	2.81	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	39.081	
1450	0.272	2.72	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.982	
1470	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.916	
1490	0.26	2.6	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.85	
1510	0.254	2.54	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.784	
1530	0.252	2.52	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.762	
1550	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.74	Best
1570	0.25	2.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.741	
1590	0.257	2.57	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.817	
1610	0.266	2.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	38.916	

Using 1:128 Splitter with 10 KM distance, it is observed that the minimum sensitivity is -38.74 dB at 1550 nm wavelength and the highest sensitivity is -39.95 dB at 1310 nm wavelength.

Table-4.15: 1:128 Splitter with 20KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	7.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	43.55	
1330	0.335	6.7	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	43.025	
1350	0.322	6.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	42.752	
1370	0.311	6.22	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	42.521	
1390	0.333	6.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	42.983	
1410	0.291	5.82	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	42.101	
1430	0.281	5.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.891	
1450	0.272	5.44	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.702	
1470	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.576	
1490	0.26	5.2	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.45	
1510	0.254	5.08	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.324	
1530	0.252	5.04	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.282	
1550	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.24	Best
1570	0.25	5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.241	
1590	0.257	5.14	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.387	
1610	0.266	5.32	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	41.576	

Using 1:128 Splitter with 20 KM distance, it is observed that the minimum sensitivity is -41.24 dB at 1550 nm wavelength and the highest sensitivity is -43.55 dB at 1310 nm wavelength.

Table-4.16: 1:128 Splitter with 30KM distance

Wave length	Attenuation (dB/km)	Attenuation for 10 m(dB)	Mux loss(dB)	Add Loss	Drop Loss	Demux Loss	Filter Loss	ODF (IN+OUT) Loss	LDP(IN+OUT) Loss	Splitter Loss	BDB (IN+OUT) Loss	ONT Loss	Total	Remarks
1310	0.36	10.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	47.15	
1330	0.335	10.05	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	46.375	
1350	0.322	9.66	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	45.972	
1370	0.311	9.33	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	45.631	
1390	0.333	9.99	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	46.313	
1410	0.291	8.73	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	45.011	
1430	0.281	8.43	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	44.701	
1450	0.272	8.16	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	44.422	
1470	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	44.236	
1490	0.26	7.8	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	44.05	
1510	0.254	7.62	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	43.864	
1530	0.252	7.56	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	43.802	
1550	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	43.74	Best
1570	0.25	7.5	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	43.741	
1590	0.257	7.71	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	43.957	
1610	0.266	7.98	0.5	1	1	0.5	8.5	0.3+0.3=0.6	0.3+0.3=0.6	24.19	0.3+0.3=0.6	0.3	44.236	

Using 1:128 Splitter with 30 KM distance, it is observed that the minimum sensitivity is -43.74 dB at 1550 nm wavelength and the highest sensitivity is -47.15 dB at 1310 nm wavelength.

From all the table, it is observed that the receiving sensitivity is minimum at 1550 nm and maximum at 1310 nm. The graphical representation is like below-

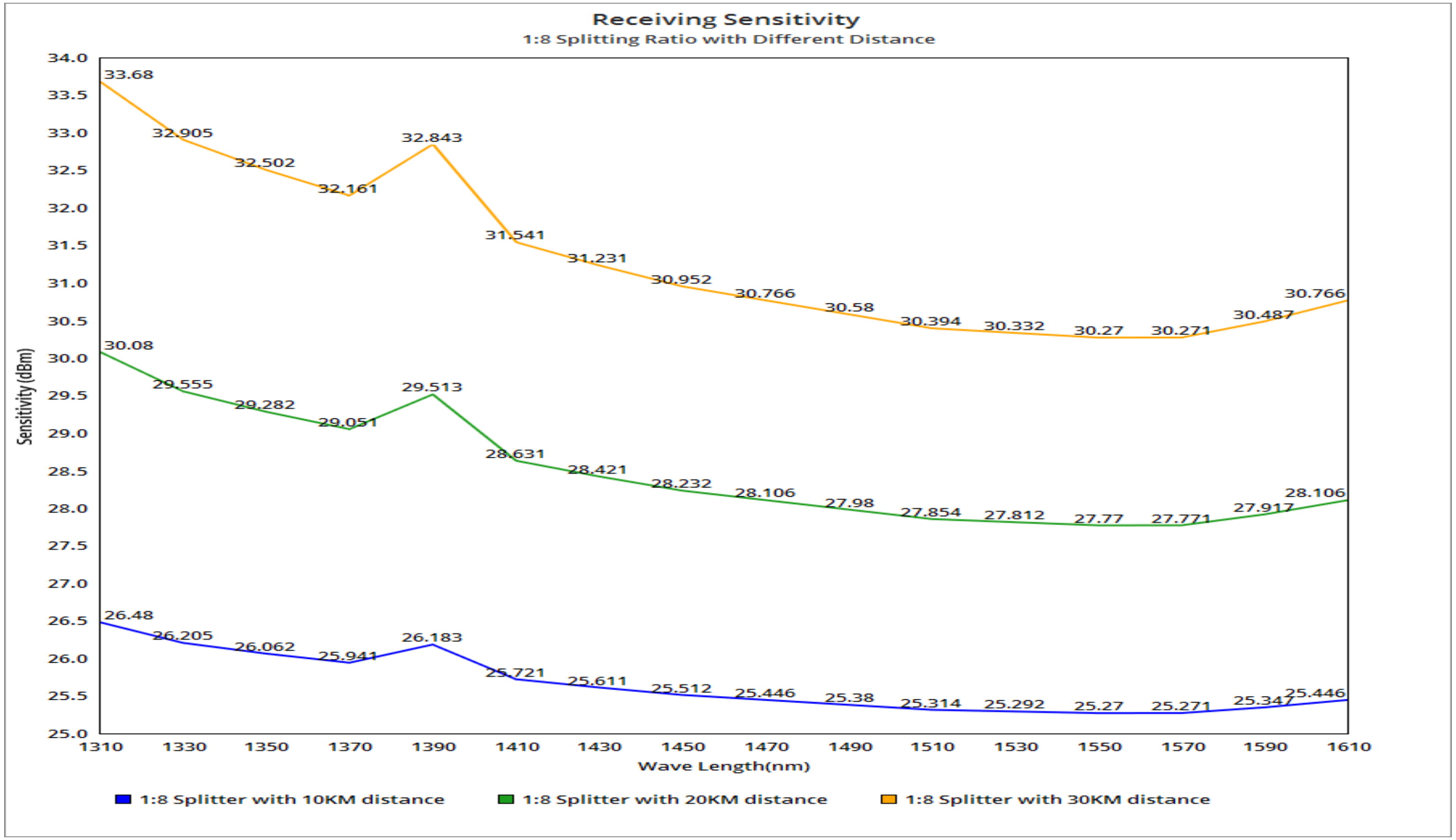


Figure-4.5: Receiving sensitivity at 1:8 Splitting with various distance

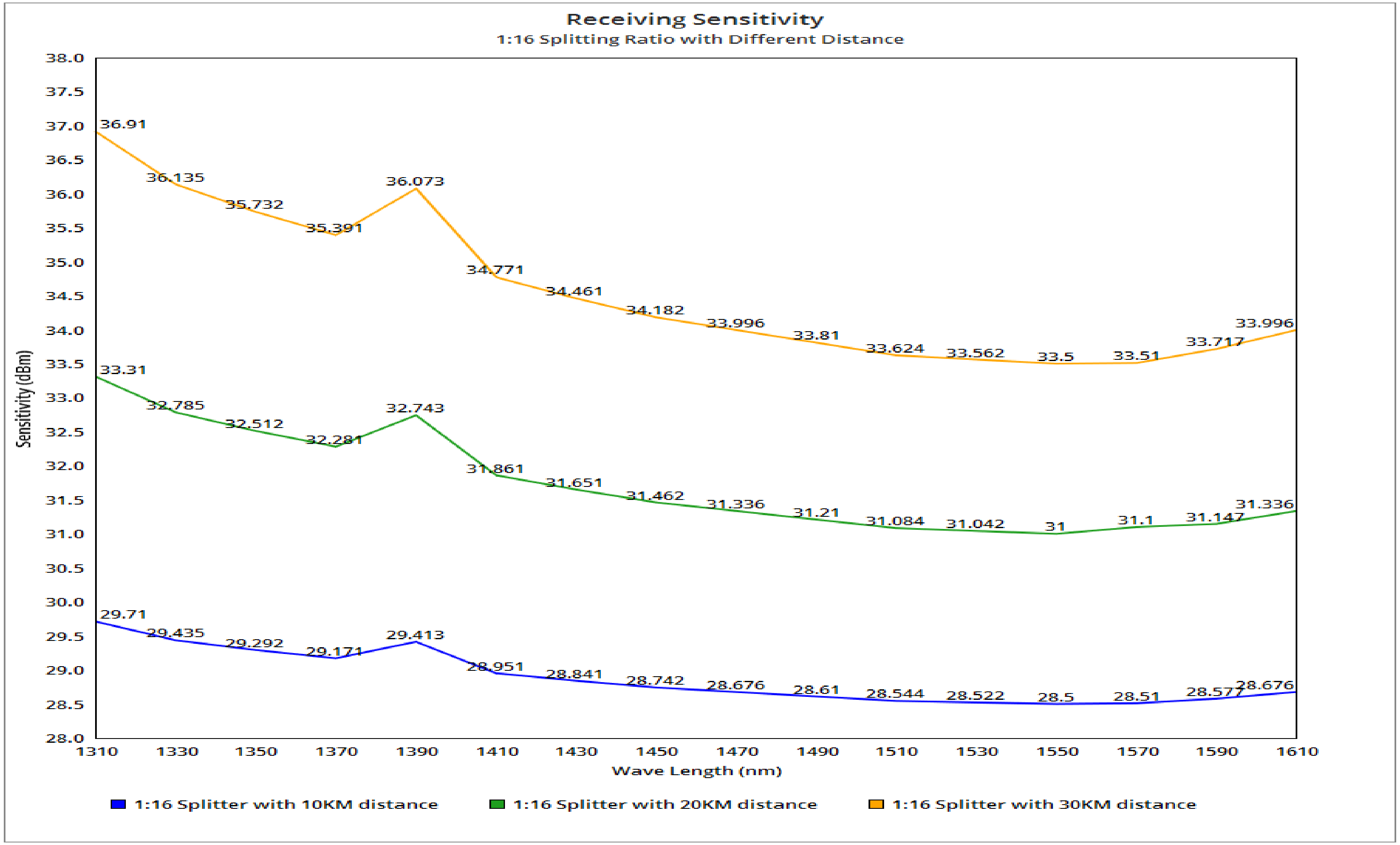


Figure-4.6: Receiving sensitivity at 1:16 Splitting with various distance

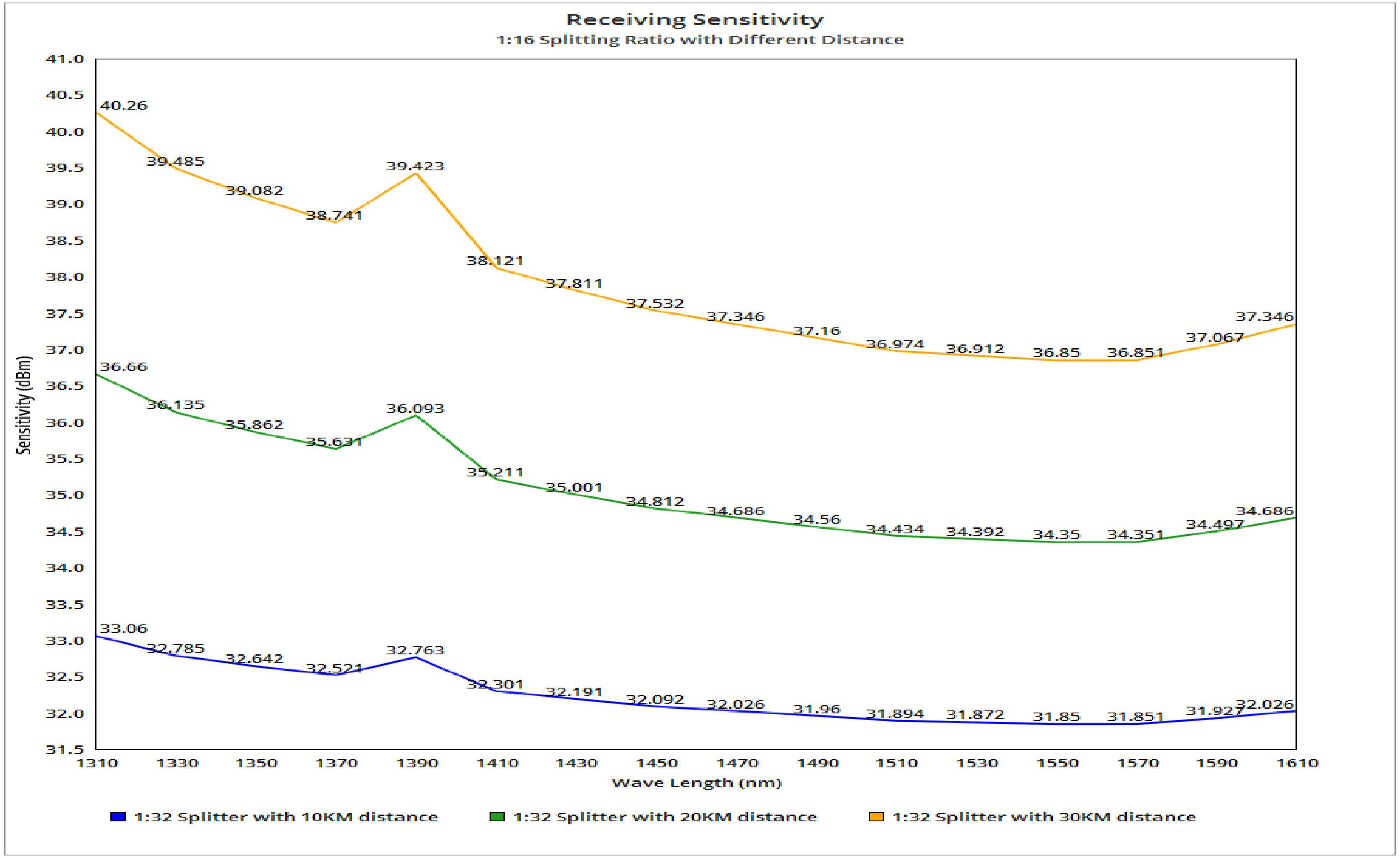


Figure-4.7: Receiving sensitivity at 1:32 Splitting with various distance

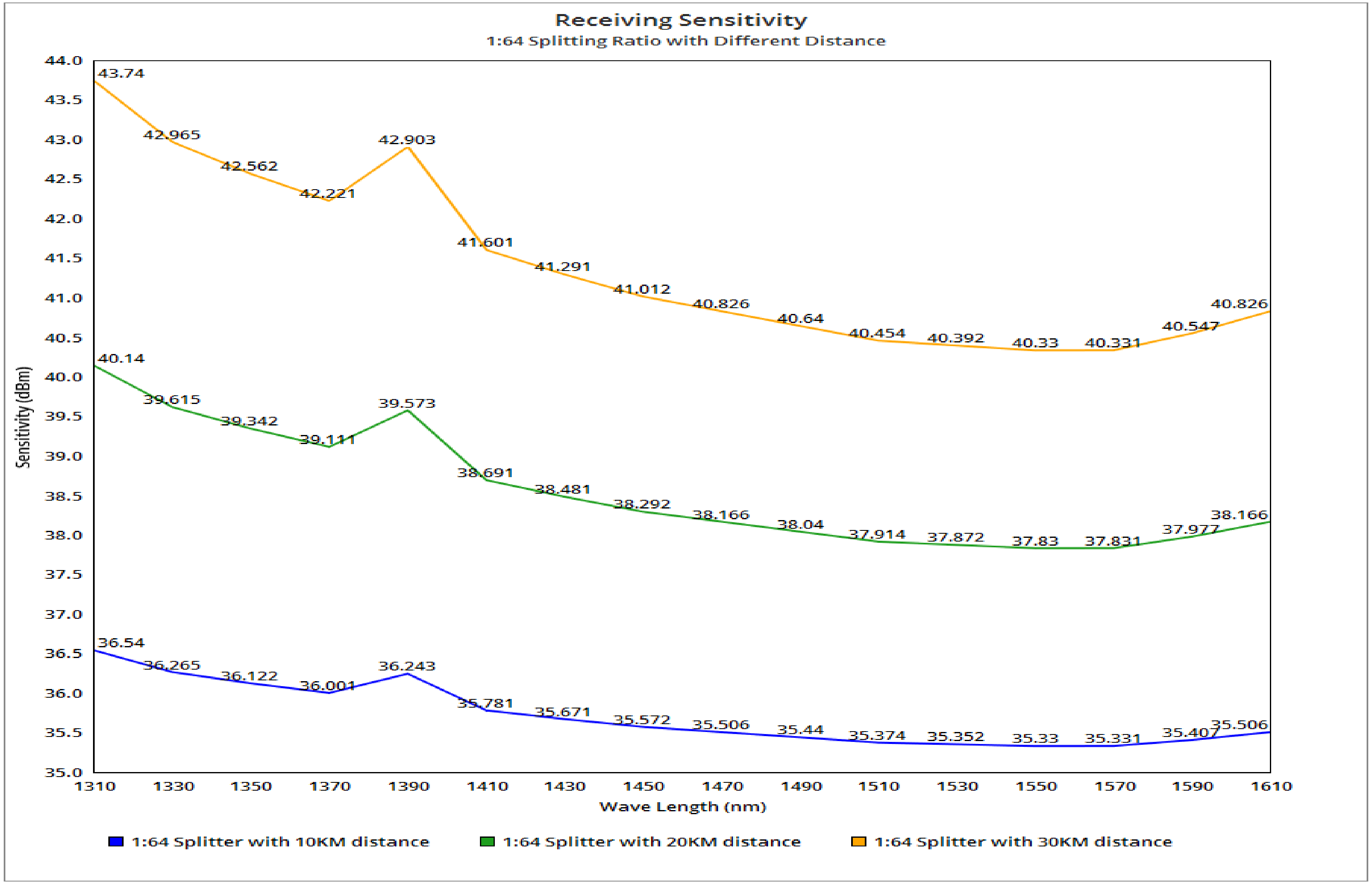


Figure-4.8: Receiving sensitivity at 1:64 Splitting with various distance

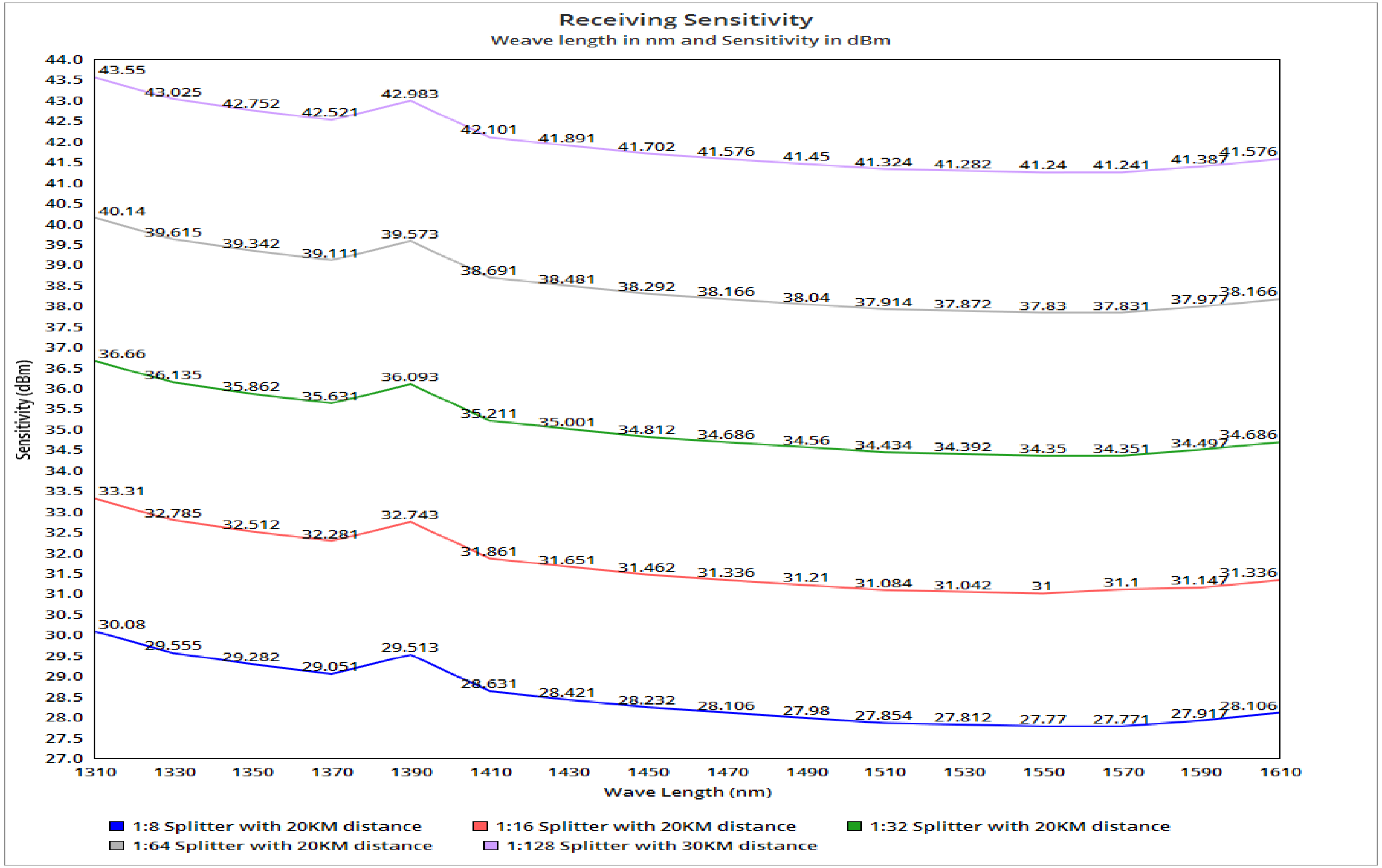


Figure-4.9: Receiving sensitivity at different Splitting ratio with various distance

4.4 Analysis

Analysing sensitivity calculation table and graph, we found that 1550 nm wavelength have sensitivity with minimum dB loss. That is, end user will get better performance. We could use 1550 nm wavelength for GPON quad play instead of using 1310 nm to 1610 nm.

4.5 Summary

In this chapter, we analyse different characteristics like- Bit Error Rate (BER), Power penalty, Crosstalk Effect and finally crosstalk effect vs wavelength. It is found that 1550 nm wavelength gives the best performance with minimum sensitivity.

Chapter 5

Simulation Environment and Results

GPON is a shared access architecture that connects customer homes via fiber to a passive optical splitter near their homes. This passive splitter is itself connected to the service provider's local exchange, where it meets the aggregation network. Unlike in the current copper world, each customer does not have a dedicated line from the aggregation network to his or her home. A GPON quad play architecture have been designed with OptSIM simulation software. ONT block and OLT block, the major block have been designed to simulate the quad play services.

5.1 Introduction

GPON technology solution is no simple matter. The stakes are considerable and the investment is supposed to drive the next 40 years of revenue or more. Vendor arguments often devolve into something like war, and as a consequence, service providers risk making their decisions on the basis of arguments that are either exaggerated or not relevant to their particular situation. This thesis aims to analysis different characteristics and to implement a GPON quad play service without EDFA combiner. We will use a MUX instead of EDFA.

5.2 GPON Quad Play Simulation Environment

The objective of this chapter is to design a simulation environment for checking GPON network access. We have designed the simulation experiment only for single user connectivity.

For this goal, the packet simulation software OptSIM has been used. OptSIM proposes hierarchical structure of pattern for creating new simulation scenarios. We define tree levels:

- Network model: It's the first level of design. It's the most abstract and generic level. The goals will be to define network topology, to define network nodes and to define the communication between each node.

- Node model: In this second level, goals are to define the functionalities for every node that has been used in the network topology. For all nodes, we built a scheme for designing internal functions with the module offered by OptSIM, and to create the specific modules required.
- Process model: The Last level. In this level, a graph is defined for modules used in the second level. The graphs specify the jobs executed by the module with the info which will be processed.

5.2.1 Network Construction

To create the simulation scenario, we have used the tree levels proposed by OptSim. We have decided to use FTTH topology (no FTTC or others) because the optical fiber arrives directly at user's home and it is the solution which offers more bandwidth capacity.

We have considered only this type of control packets in our simulation and we didn't consider others features related to delays or protocols since the objectives of our analysis need only results about bandwidth consumption due to medium access control procedures.

5.2.2 ONU/ ONT Design

User's ONT consists of splitter, and data receiver and video receivers. Data receiver is configured with optical filter, PIN/TIA receiver, and BER Tester. The video signal receiver consists of optical filter, PIN/TIA receiver and electrical filters.

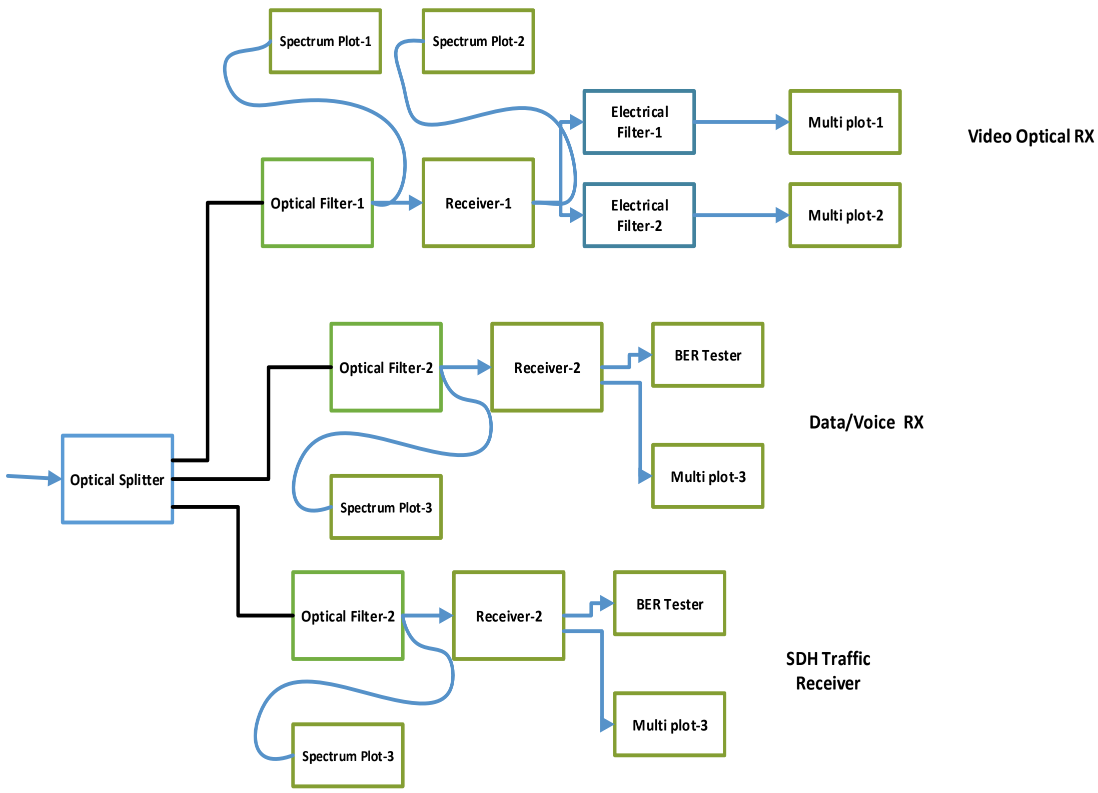


Figure-5.1: Block Diagram of ONU/ONT

5.2.3 OLT Design

First, we describe in details the configurations for Central Office OLT and single end-user ONT and then, will generalize the treatment to all 16 uses. In this experiment, we consider downstream configuration of GPON with bitrate 1.25 Gb/s and support for quad-play. The quad-play service is realized as a combination of SDH traffic, data, voice, and video signals. The high-speed Internet component is represented by a data link with 1.25 Gb/s downstream bandwidth. The voice component can be represented as VOIP service (voice over IP, packet-switched protocol) and can be combined with data component in physical layer simulations. Finally, the video component can be represented as a RF video signal (traditional CATV) or as IPTV signal that also can be combined with data. In our case, we consider the former case with RF video link. To optimize the bandwidth in PON, the transmission through the optical fiber path employs the CWDM technique with data/voice component transmitted at wavelengths in the range of 1480-1500 nm, and video within the 1550-1560 nm range [49].

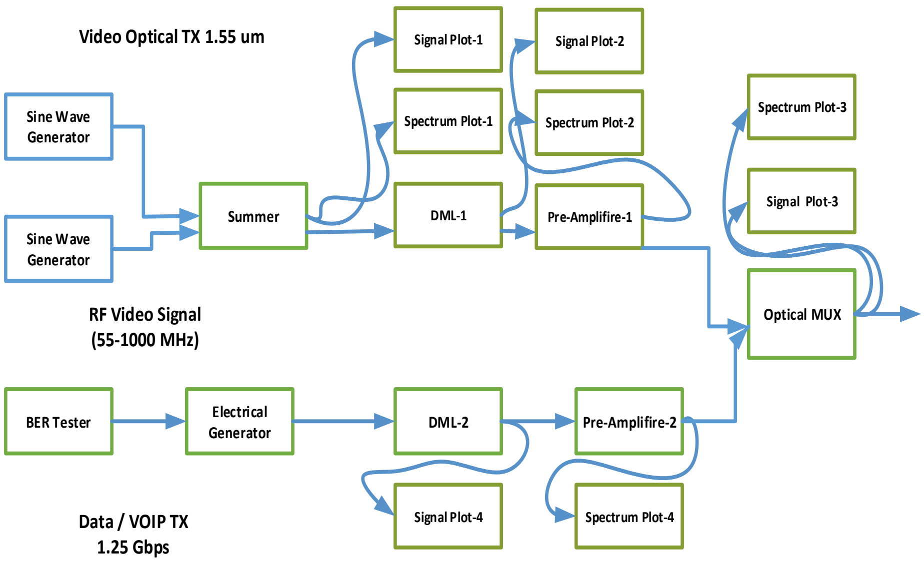


Figure-5.2: Block Diagram of OLT

CO OLT block (Transmitter block) consists of Data/VOIP and Video components. The Data/VOIP transmitter modeled with pseudo-random data generator (PRBS), NRZ modulator driver, direct-modulated laser, and booster amplifier. The video component modeled as RF SCM (sub-curricer multiplexed) link with only two tones (channels) for simplicity. The two channels we used are from standard NTSC analog CATV frequency plan - channel 2 and channel 78 at frequencies 55.25 MHz and 547.25 MHz, respectively. RF video transmitter consists of two Electrical Signal Generators, summer, direct-modulated laser, and pre-amplifier. Next, Data/Voice and Video signals are multiplexed at Multiplexer and launched into 20-km fiber span. Output from the fiber trunk goes through the 1:16 splitter and then to individual users. User's ONT consists of splitter and data and video receivers. Data receiver configured with optical filter, PIN/TIA receiver, and BER Tester. The video signal receiver consists of optical filter, PIN/TIA receiver and electrical filters [49].

5.3 Results Analysis

The input and output signal of general triple play architecture and the proposed quad play architecture are given below-

The input and output signal of general triple play architecture and the proposed quad play architecture are given below-

5.3.1 Data and Voice signal for wavelength-1310 nm

At first data, voice and video signal combinedly enter in to OLT and here, all signals are in same wave length (1310nm). In general triple play, the signal will be modulated at OLT but in proposed quad play architecture, the combined signal will be modulated at MUX and the modulated signal will propagate through OLT.

General Triple Play:

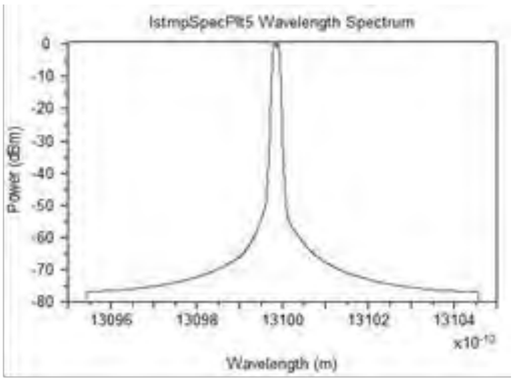


Figure-5.3: Input Signal (1310 nm)(Triple Play)

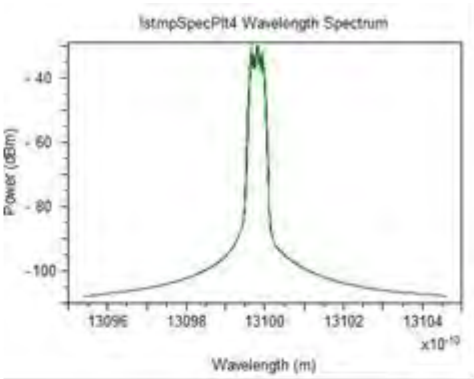


Figure-5.4: Output Signal (1310 nm) (Triple play)

Proposed Quad Play(QP):

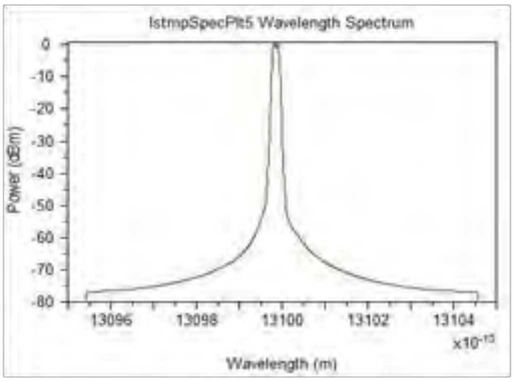


Figure-5.5: Input Signal (1310 nm)(Quad Play)

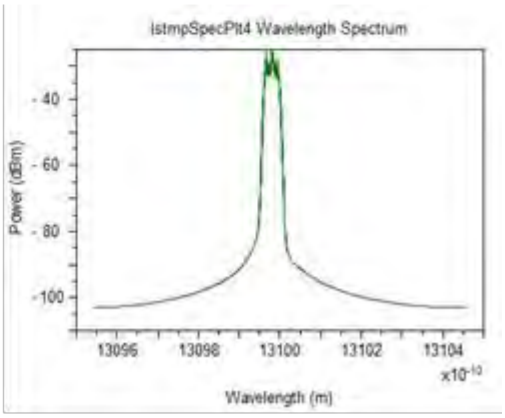
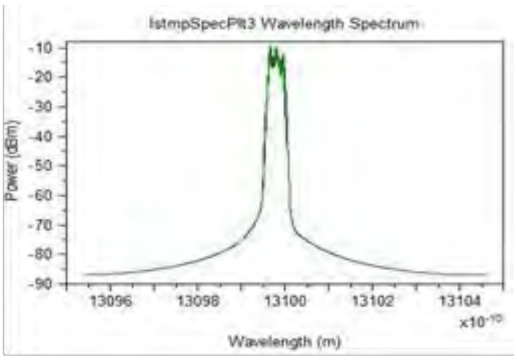


Figure-5.6: Output Signal (1310 nm)(Quad Play)

The signal graph (Figure-5.3,5.4,5.5 and 5.6), it is shown as power losses in dBm vs wavelength. From the figure, we see that input signal is propagates at 0dBm loss and the out signal gets at approximately -30dBm loss. But in proposed quad play architecture, the output signal gets at approximately -25dBm. Here, the output signal's receiving sensitivity is approximately -30dBm at general triple play whereas approximately -25dBm at proposed quad play.

5.3.2 Video signal for Wavelength 1310 nm

General Triple play (TP):



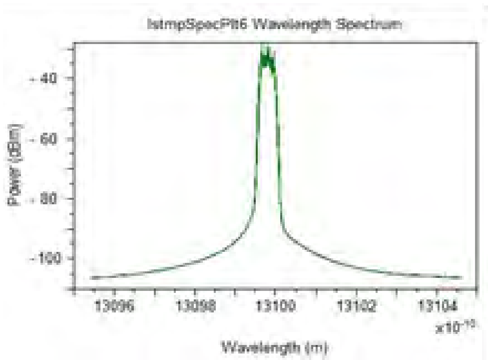
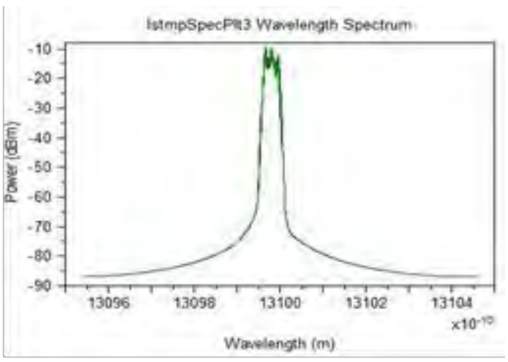


Figure-5.7: Video Input Signal (1310 nm)(TP) Figure-5.8: Video Output Signal (1310 nm)(TP)

Proposed Quad Play:



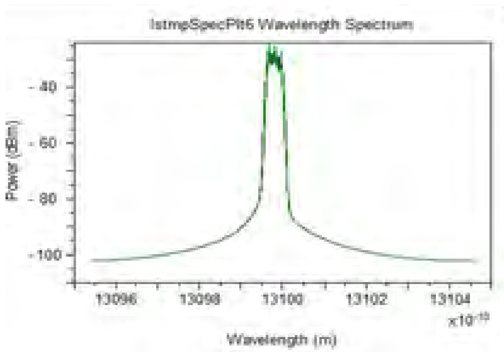


Figure-5.9: Video Input Signal (1310 nm) (QP) Figure-5.10: Video Output Signal (1310 nm)(QP)

The video input signal propagates at -10dBm through the OLT and its output signal is at approximately -30dBm at general triple play while approximately -26 dBm is at proposed quad play. Here, we are getting better output signal.

SDH Traffic:

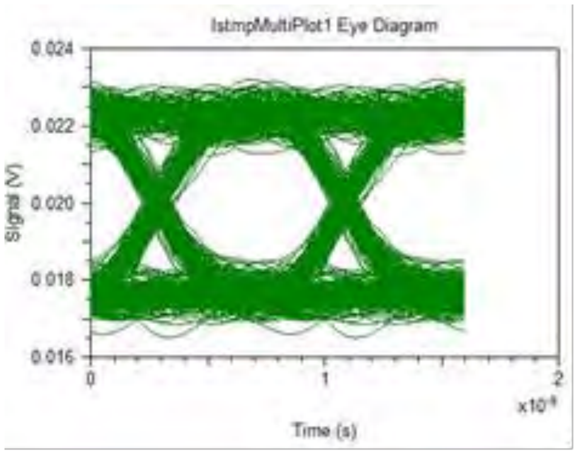


Figure-5.11: Eye Diagram of SDH Traffic (QP)

In figure-5.11, an eye diagram shows the SDH traffic. In general triple play architecture, the SDH traffic is absent but in the proposed quad play architecture, the SDH traffic could be measured by the ONT's ethernet port.

5.3.3 Data and Voice signal for Wavelength 1490 nm

At first data, voice and video signal combinedly enter into OLT and here all signals are in same wavelength (1490 nm). In general triple play, the signal will be modulated at OLT, but in proposed quad play architecture, the combined signal will be modulated at MUX and the modulated signal will propagate through OLT.

General Triple Play:

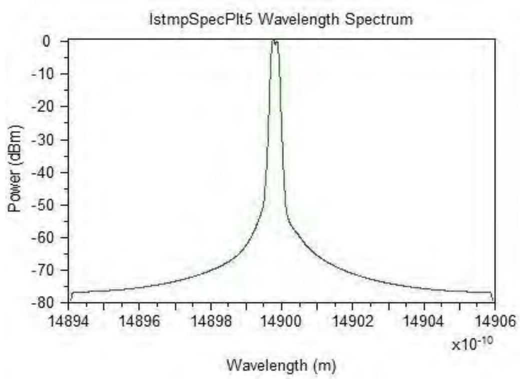


Figure-5.12: Input Signal (1490 nm)(TP)

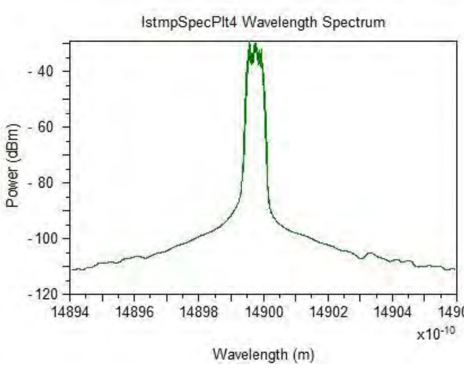
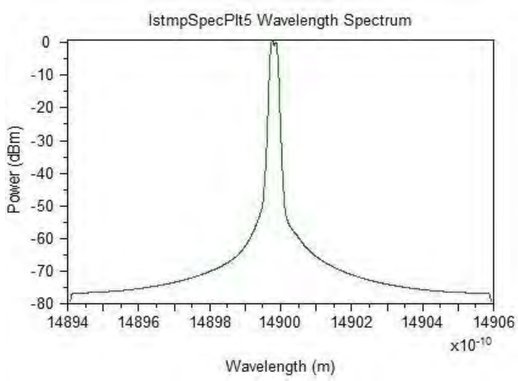


Figure-5.13: Output Signal (1490 nm)(TP)

Proposed Quad Play:



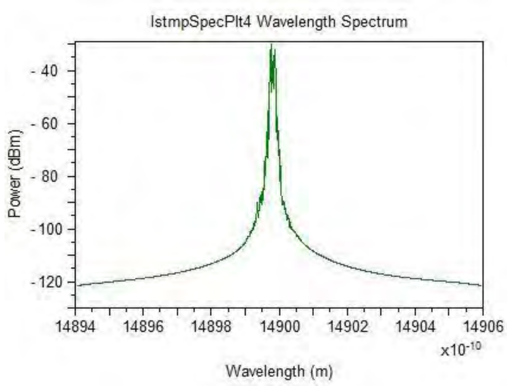


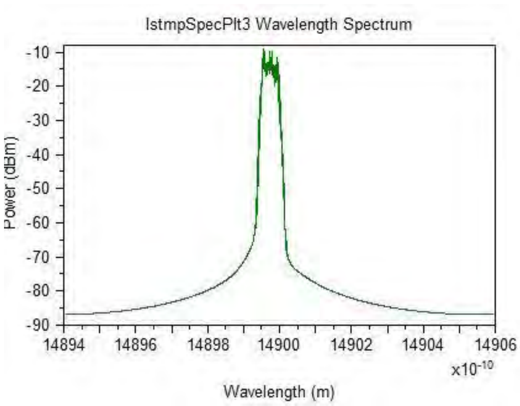
Figure-5.14: Input Signal (1490 nm)(QP)

Figure-5.15: Output Signal (1490 nm)(QP)

The signal graph is shown in figure-5.12,5.13,5.14 and 5.15, as power losses in dBm vs wavelength. Figure shows that input signal propagates at 0dBm loss and the out signal gets at approximately -30dBm loss. But, in proposed quad play architecture, the output signal gets at approximately -25dBm. Here, the output signal's receiving sensitivity is approximately -30 dBm at general triple play whereas -30 dBm at proposed quad play.

5.3.4 Video signal for Wavelength 1490 nm

General Triple Play:



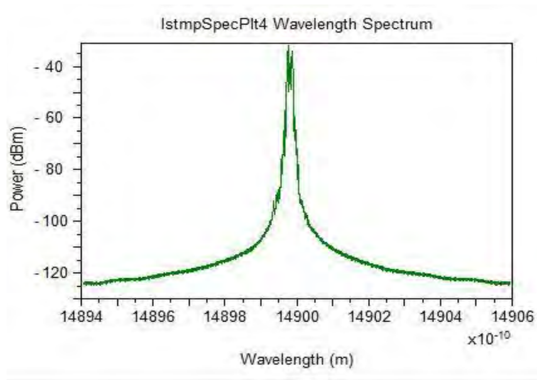


Figure-5.16: Video Input Signal (1490 nm)(TP)

Figure-5.17: Video Output Signal (1490 nm)(TP)

Proposed Quad Play:

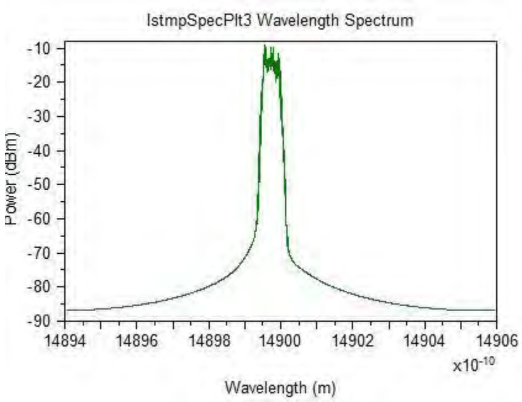


Figure-5.18: Video Input Signal (1490 nm)(QP)

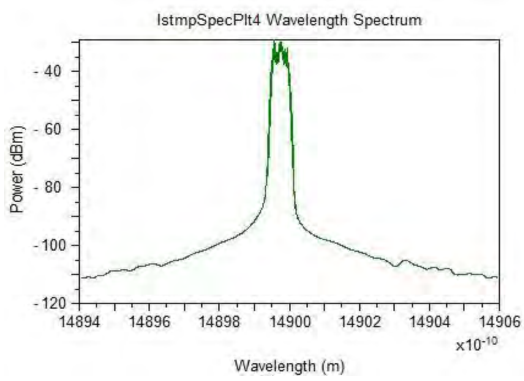


Figure-5.19: Video Output Signal (1490 nm)(QP)

The video input signal propagates at -10dBm through the OLT and its output signal is at approximately -32 dBm at general triple play while approximately -30dBm is at proposed quad play. Here, we are getting better output signal.

SDH Traffic:

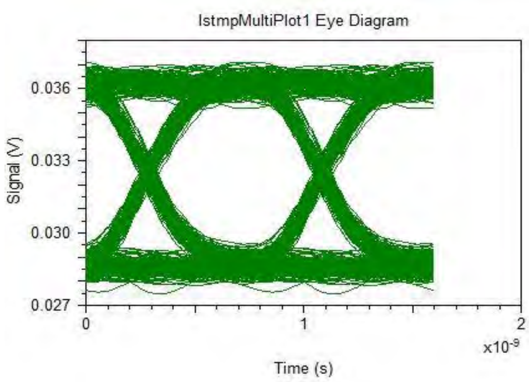


Figure-5.20: Eye Diagram of SDH Traffic (QP)

Figure-5.20, an eye diagram shows the SDH traffic. In general triple play architecture, the SDH traffic is absent but in the proposed quad play architecture, the SDH traffic could be measured by the ONT's ethernet port.

5.3.4 Data and Voice signal for Wavelength 1550 nm

At first data, voice and video signal combinedly enter in to OLT and here, all signals are in same wavelength (1550 nm). In general triple play, the signal will be modulated at OLT, but in proposed quad play architecture, the combined signal will be modulated at MUX and the modulated signal will propagate through OLT.

General Triple Play:

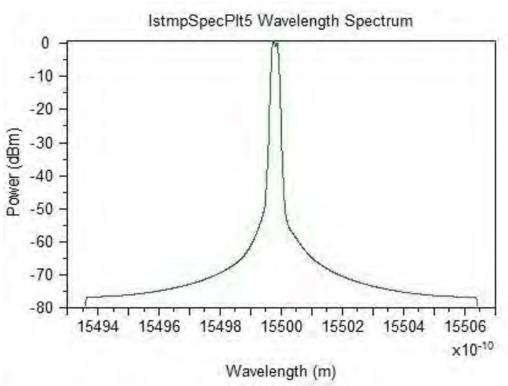


Figure-5.21: Input Signal (1550 nm)(TP)

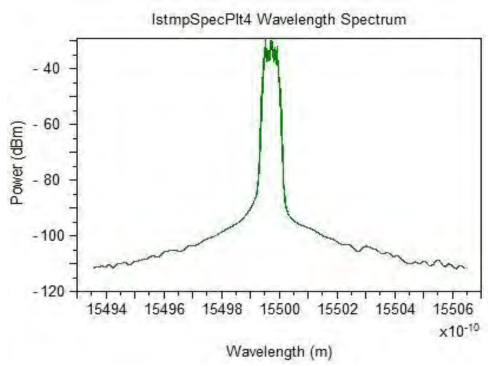


Figure-5.22: Output Signal (1550 nm)(TP)

Proposed Quad Play:

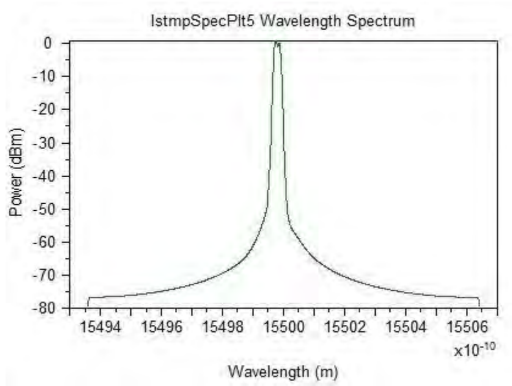


Figure-5.23: Input Signal (1550 nm)(QP)

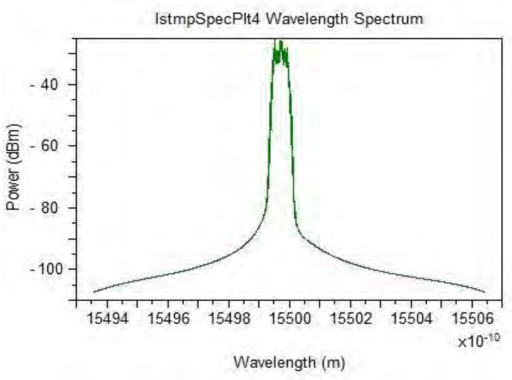
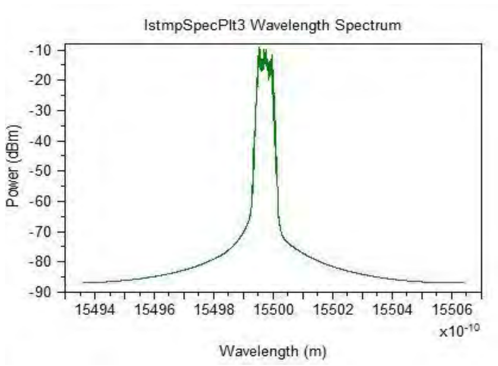


Figure-5.24: Output Signal (1550 nm)(QP)

The signal graph shown in figure-5.21,5.22,5.23 and 5.24, as power losses in dBm vs wavelength. Figures show that input signal is propagates at 0dBm loss and the out signal gets at -30dBm loss. But in proposed quad play architecture the output signal gets at approximately -25dBm. Here, the output signal's receiving sensitivity is approximately -30dBm at general triple play whereas approximately -25dBm at proposed quad play.

5.3.6 Video signal for Wavelength 1550 nm

General Triple Play:



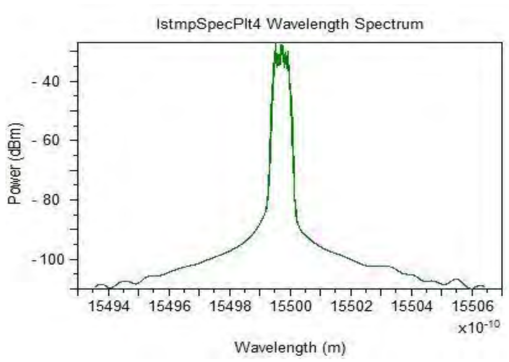
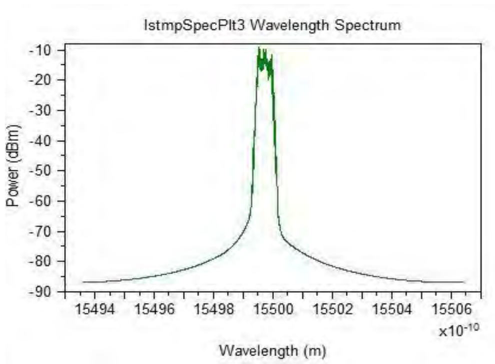


Figure-5.25: Video Input Signal (1550 nm)(TP) Figure-5.26: Video Output Signal (1550 nm)(TP)

Proposed Quad Play:



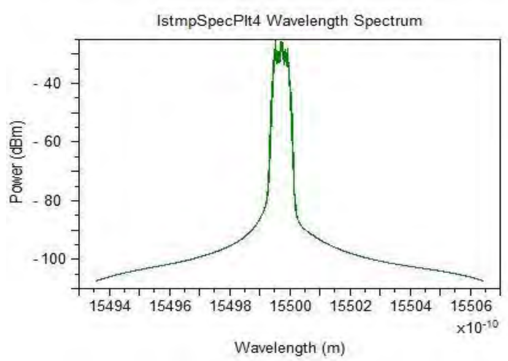


Figure-5.27: Video Input Signal (1550 nm)(QP) Figure-5.28: Video Output Signal (1550 nm)(QP)

The video input signal propagates at -10 dBm through the OLT and its output signal is at approximately -32dBm at general triple play while approximately -29 dBm at proposed quad play. Here, we are getting better output signal.

SDH Traffic:

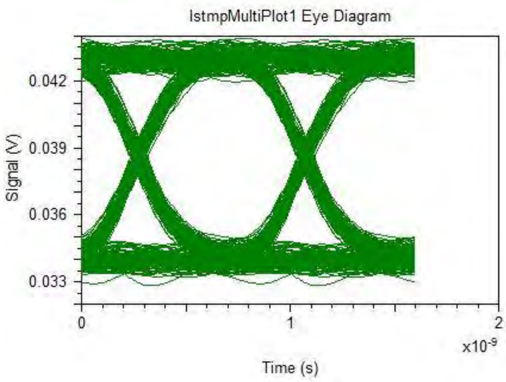


Figure-5.29: Eye Diagram of SDH Traffic(QP)

In figure-5.29, the SDH traffic is shown by an eye diagram. In general triple play architecture, the SDH traffic is absent but in the proposed quad play architecture, the SDH traffic could be measured by the ONT's ethernet port. If the noise increased, then the eye will become smaller.

5.3.7 Data and Voice signal for Wavelength 1490 nm and video signal for wavelength 1310 nm (Combinedly)

In this scenario, the voice and data signals are at 1490 nm and the video signal at 1310 nm. The signal will be modulated at OLT in general triple play system, but in MUX at proposed quad play system. From proposed quad play system, there is an SDH output taken from the ONT's ethernet port.

Data and Voice (1490 nm):

General Triple Play:

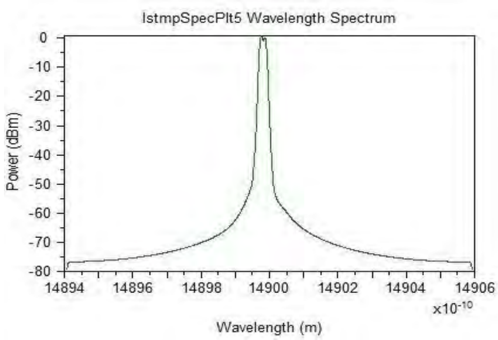


Figure-5.30: Input Signal (1490 nm)(TP)

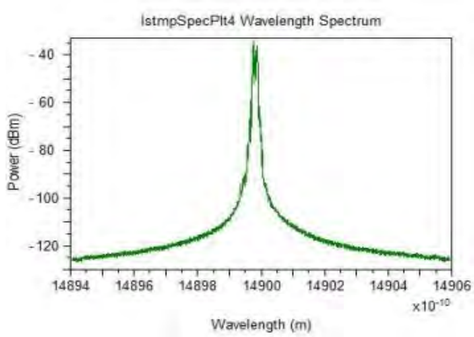


Figure-5.31: Output Signal (1490 nm)(TP)

Proposed Quad play:

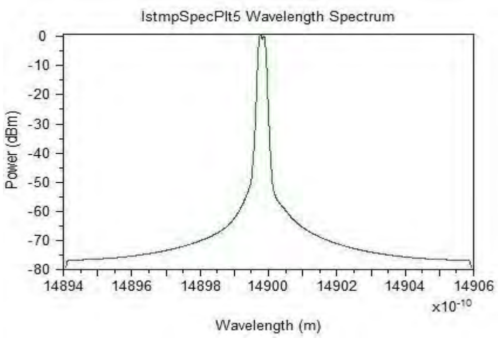


Figure-5.32: Input Signal (1490 nm)(QP)

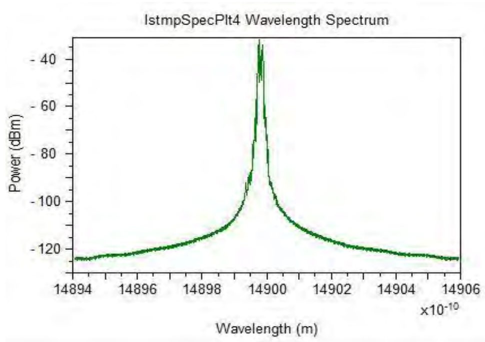


Figure-5.33: Output Signal (1490 nm)(QP)

The signal graphs are shown in figure-5.30, 5.31, 5.32 and 5.33, as power losses in dBm vs wavelength. Figure-5.31 shows that input signal propagates at 0dBm loss and the output signal gets at approximately -34dBm loss. But in proposed quad play architecture, the output signal gets at approximately -32dBm. Here, the output signal's receiving sensitivity is approximately -34dBm at general triple play whereas approximately -32dBm at proposed quad play.

<u>Video (1310 nm):</u>

General Triple Play:

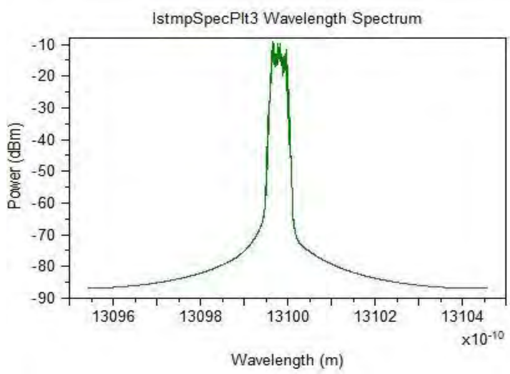


Figure-5.34: Video Input Signal (1310 nm)(TP)

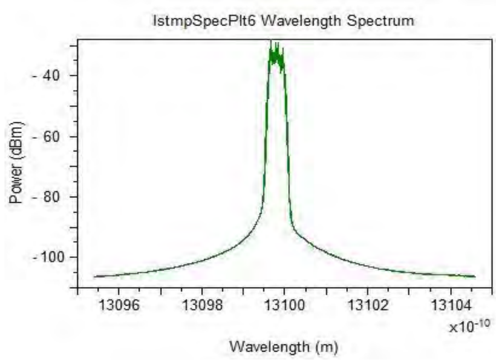


Figure-5.35: Video Output Signal (1310 nm)(TP)

Proposed Quad play:

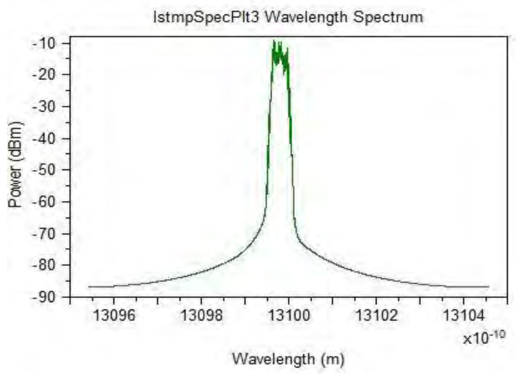


Figure-5.36: Video Input Signal (1310 nm)(QP)

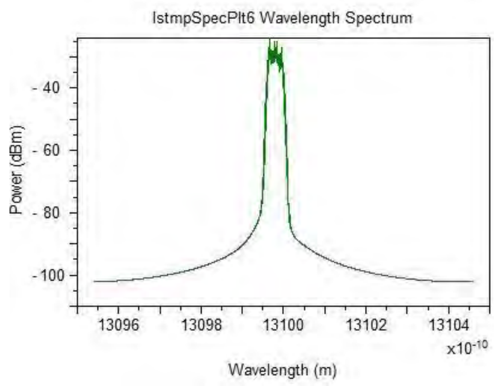


Figure-5.37: Video Output Signal (1310 nm)(QP)

The video input signal propagates at approximately -10dBm through the OLT and its output signal is at approximately -29dBm at general triple play while approximately -35 dBm at proposed quad play. Here, we are getting better output signal.

SDH traffic:

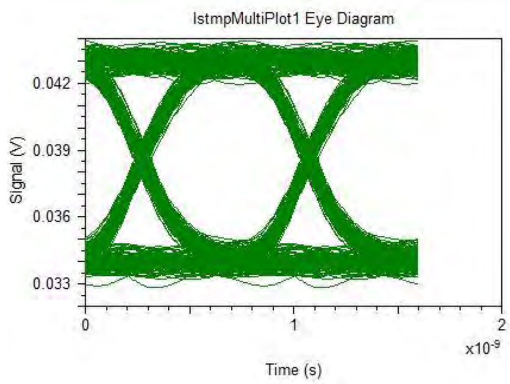


Figure-5.38: Eye Diagram of SDH Traffic(QP)

If the eye becomes shorter, the noise increased. From the above figure-5.38, it could say that the SDH traffic carry a few noises. The eye is sharper.

5.3.8 Data and Voice signal for Wavelength 1550 nm and video signal for wavelength 1310 nm (Combinedly)

In this scenario, the voice and data signals are at 1550 nm and the video signal is at 1310 nm. The signal will be modulated at OLT in general triple play system, but in MUX, at proposed quad play system. From proposed quad play system, there is an SDH output taken from the ONT’s ethernet port.

Data and Voice (1550 nm):

General Triple Play:

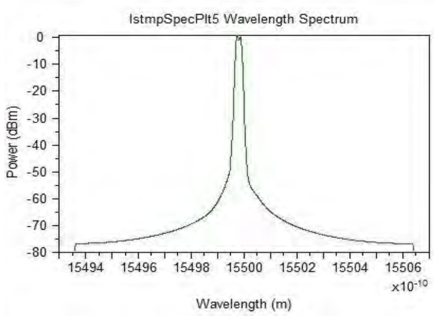


Figure-5.39: Input Signal (1550 nm)(TP)

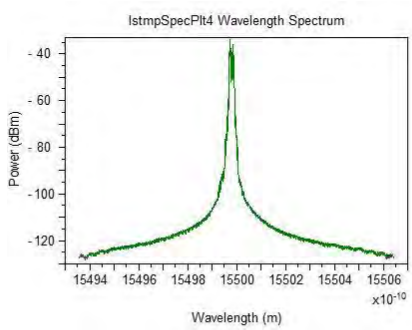


Figure-5.41: Output Signal (1550 nm)(TP)

Proposed Quad play:

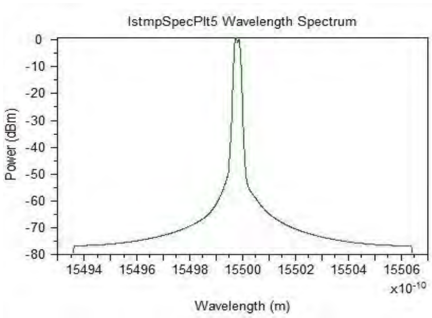


Figure-5.41: Input Signal (1550 nm)(QP)

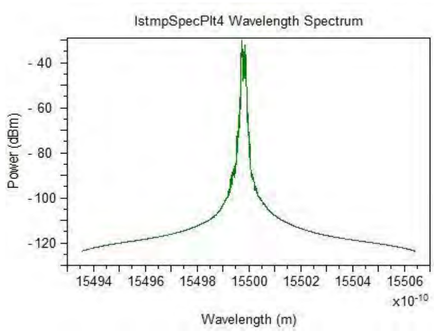


Figure-5.42: Output Signal (1550 nm)(QP)

The signal graph is shown as power losses in dBm vs wavelength. From the figure shown that input signal is propagates at 0dBm loss and the out signal gets at -35dBm loss. But in proposed quad play architecture the output signal gets at approximately -30dBm. Here, the output signal's receiving sensitivity is approximately -35dBm at general triple play whereas approximately -30dBm at proposed quad play.

Video (1310 nm):

General Triple Play:

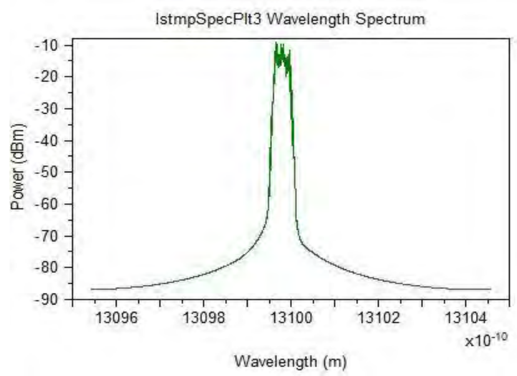


Figure-5.43:Video Input Signal (1310 nm)(TP)

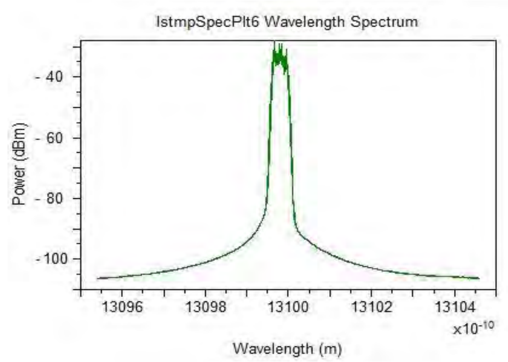


Figure-5.44: Video Output Signal (1310 nm)(TP)

Proposed Quad play:

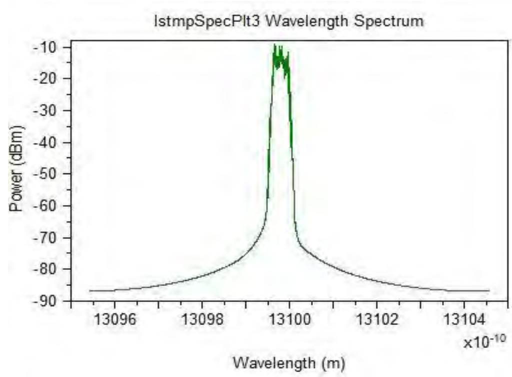


Figure-5.45: Video Input Signal (1310 nm)(QP)

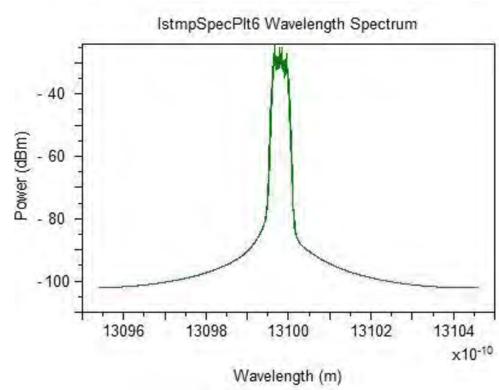


Figure-5.46: Video Output Signal (1310 nm)(QP)

The video input signal propagates at approximately -10dBm through the OLT and its output signal is at approximately -29dBm at general triple play while approximately -27 dBm is at proposed quad play. Here, we are getting better output signal.

SDH traffic:

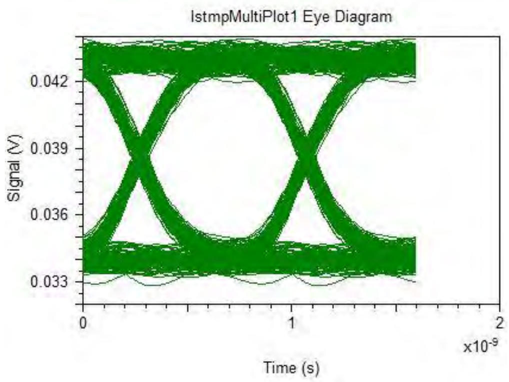


Figure-5.47: Eye Diagram of SDH Traffic(QP)

If the eye becomes shorter, the noise increased. From the above figure-5.47, it could say that the SDH traffic carry a few noises. The eye is sharper. It is almost noise free eye diagram.

5.3.9 Data and Voice Signal for Wavelength 1490 nm and Video Signal for Wavelength 1550 nm (Combinedly)

In this scenario, the voice and data signals are at 1490 nm and the video signal at 1550 nm. The signal will be modulated at OLT in general triple play system, but in MUX, at proposed quad play system. From proposed quad play system, there is an SDH output taken from the ONT's ethernet port.

<u>**Data and Voice (1490 nm):**</u>

General Triple Play:

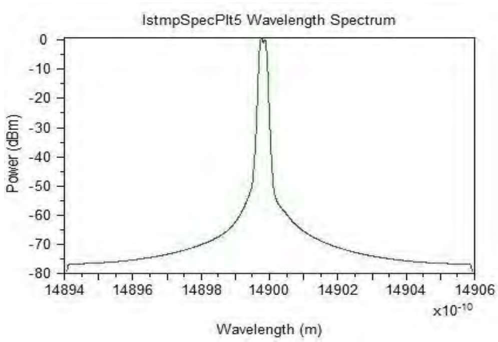


Figure-5.48: Input Signal (1490 nm)(TP)

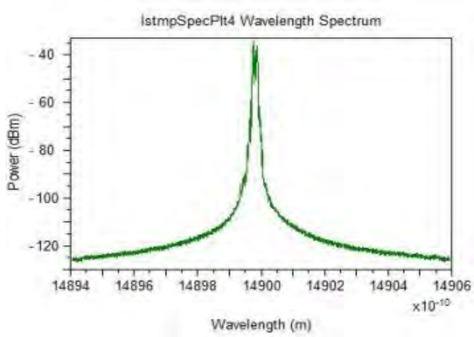


Figure-5.49: Output Signal (1490 nm)(TP)

Proposed Quad play:

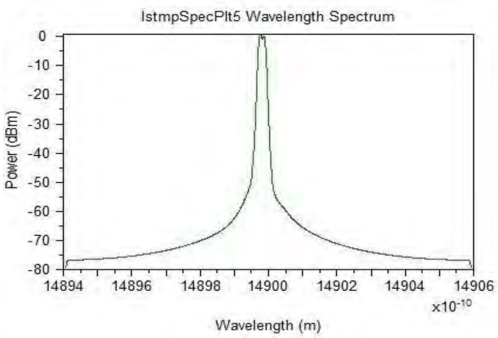


Figure-5.50: Input Signal (1490 nm)(QP)

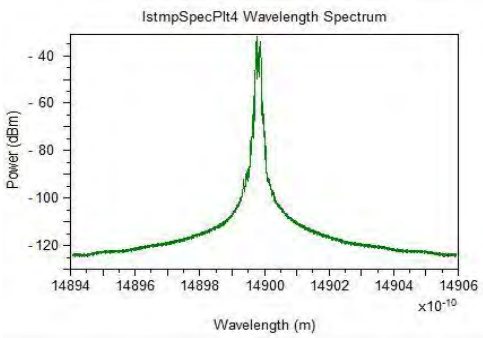


Figure-5.51: Output Signal (1490 nm)(QP)

The signal graph is shown as power losses in dBm vs wavelength. From the figure shown that input signal is propagates at 0dBm loss and the out signal gets at approximately -35dBm loss. But in proposed quad play architecture the output signal gets at approximately -38dBm. Here, the output signal's receiving sensitivity is approximately -35dBm at general triple play whereas approximately -38dBm at proposed quad play.

Video (1550 nm):

General Triple Play:

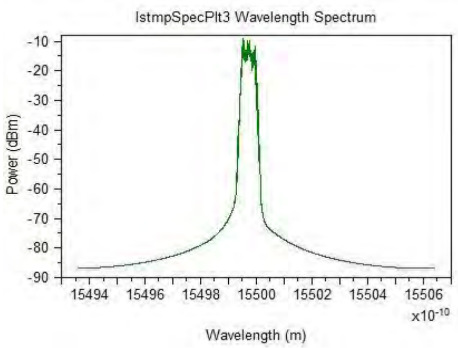


Figure-5.52: Video Input Signal (1550 nm)(TP)

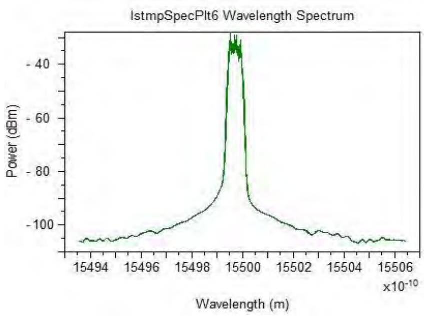


Figure-5.53: Video Output Signal (1550 nm)(TP)

Proposed Quad play:

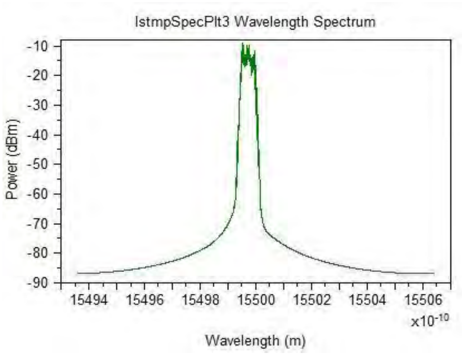


Figure-5.54: Video Input Signal (1550 nm)(QP)

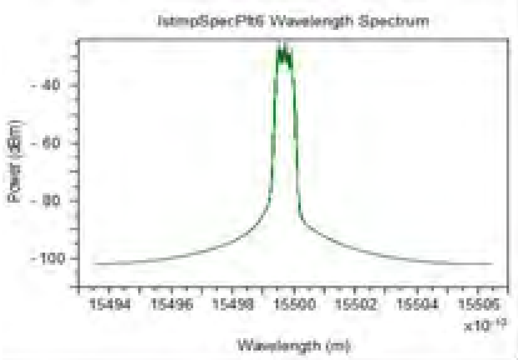


Figure-5.55: Video Output Signal (1550 nm)(QP)

The video input signal propagates at approximately -10 dBm through the OLT and its output signal is at approximately -34dBm at general triple play while approximately -27dBm is at proposed quad play. Here, we are getting better output signal compare to general triple play.

SDH traffic:

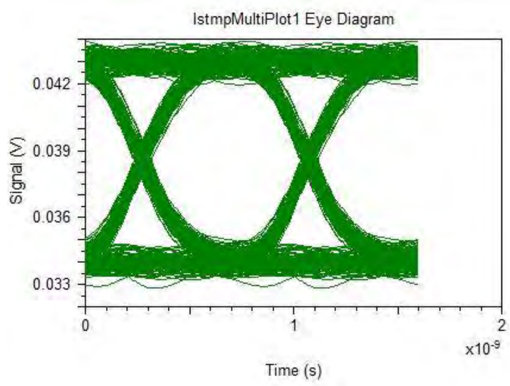


Figure-5.56: Eye Diagram of SDH Traffic(QP)

In general triple play services, the eye diagram could not measure, but in proposed quad play, we can easily measure the eye diagram from ONT/ONU's ethernet port. Figure-5.56 shows that almost noise free traffic could be captured from quad play architecture.

Analysing in terms of 1550 nm wavelength, we found the following figures.

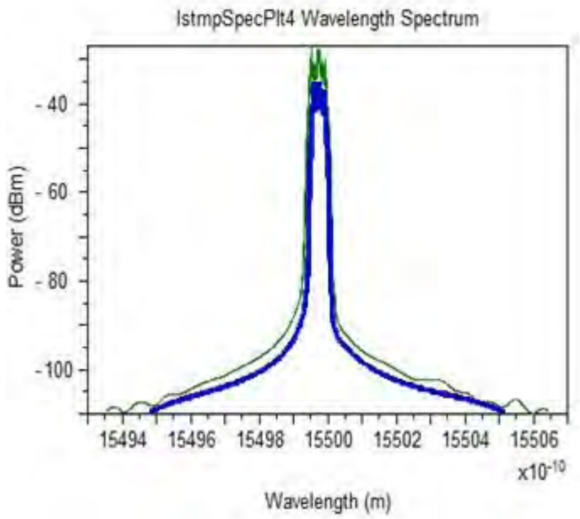


Figure-5.57: Data Output Signal for Quad play vs Triple Play for 1550 nm

In the figure-5.57, the blue line shows the general triple play sensitivity and the green line shows the proposed quad play sensitivity. General triple play has approximately -30 dBm power loss while proposed quad play has approximately -25 dBm.

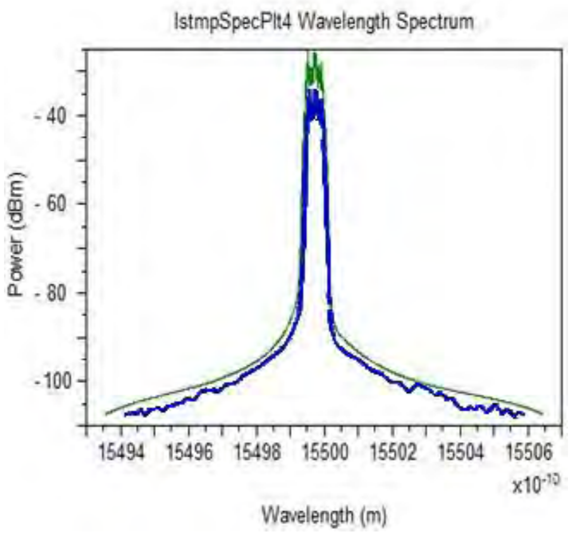


Figure-5.58: Video Output Signal for Quad play vs Triple Play for 1550 nm

In the figure-5.58, the blue line shows the general triple play sensitivity and the green line shows the proposed quad play sensitivity. General triple play has approximately -35 dBm power loss while Proposed quad play has approximately -32 dBm.

From the previous analysis, we found that 1550 nm gives the best performance which we have analysed theatrically and analytically in chapter 3 and chapter 4.

5.4 BER Analysis for Quad Play vs Triple Play

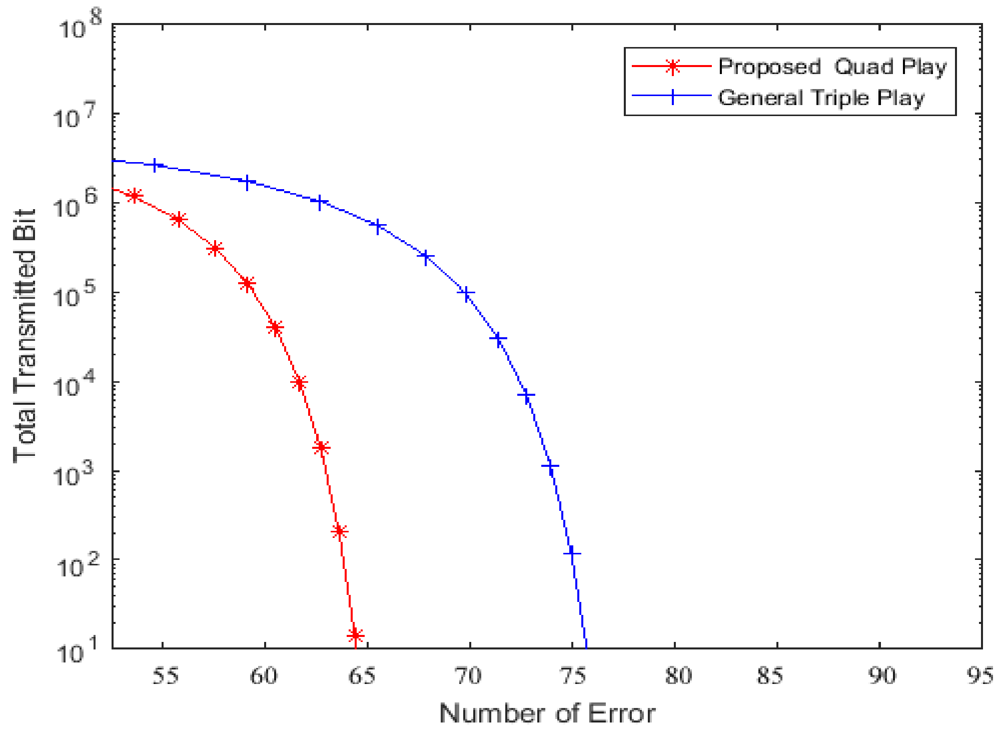


Figure-5.59: Total transmitted bit vs Number of Error

From the above figure-5.59, we found that for every 1 Mega bit transmission there are 64 bit error in proposed quad play while 76 bit error in general triple play. If the number of transmitted bit increased, then the Number of error will also increase in triple play, but in proposed quad play the error bit will not increase in the same ratio compare to triple play.

Table-5.1: Comparison of different wavelength with dB gain in Quad Play

SN	Wavelength (nm)			Input (dBm)	Output (dBm)		Gain (dBm)	Remarks
	Voice	Data	Video	V=Video	Triple Play (TP)	Quad Play (QP)	(TP-QP)	
1	1310	1310	1310	0, -10 (V)	-30, -26 (V)	-27, -26(V)	3, 0 (V)	
2	1490	1490	1490	0, -10 (V)	-30, -32 (V)	-30, -30(V)	0, 2(V)	
3	1550	1550	1550	0, -10 (V)	-30, -32 (V)	-25, -29(V)	5, 3 (V)	Best
4	1490	1490	1310	0, -10 (V)	-34, -29 (V)	-32, -35(V)	2, 6 (V)	
5	1550	1550	1310	0, -10 (V)	-35, -29 (V)	-30, -27(V)	5, 2 (V)	
6	1490	1490	1550	0, -10 (V)	-35, -34 (V)	-38, -27(V)	3, 7 (V)	

Form the above table-5.1, we can summarise that, if we use 1550 nm wavelength for GPON quad play services, we gain approximately -5 dB for data and voice, approximately -3 dB for video and these are the best gain compare to other wavelengths at GPON triple play services.

5.5 Outcome of the Experiments

Our main interest was to find out the best wavelength for GPON quad play solution with high performance. Now, typical triple play solution is running by a mixed wavelength. Here, **1310 nm to 1550 nm** wavelength is used for triple play connectivity. Sometimes, it makes some interference within clients. We were keen to find out a single wavelength instead of multiple wavelength. Analysing all possible combinations, we found that for quad play architecture, 1550 nm wavelength gives better eye diagram for SDH traffic and better performance in data, voice and video service.

5.6 Summary

In this chapter, we discussed about the analysis of GPON quad play architecture and simulation results. Finally, we found that 1550 nm wavelength is the best for GPON quad play services.

Chapter 6

Conclusion and Future Work

In this final chapter, we summarize the conclusion that can be drawn from the research that is carried out thesis and then provide suggestions for direction of future work.

6.1 Conclusion of this Study

Through our research methodology, we have performed the following:

(i) Analysed and measured various parameter of DWDM and CWDM technology;
(ii) Mathematically analysed the cross-talk effect, Bit Error Rate (BER), Power Penalty and found out the noise figure of DWDM and CWDM technology;
(iii) Found the best lowest receiving sensitivity against wavelength and prepared Sensitivity calculation table.
(iv) Proposed and simulated a quad play architecture without EDFA combiner (using MUX) with CWDM technology;
(v) Verified the simulation results with theoretical analysis.

Using a MUX instead of EDFA combiner, we have proposed and simulated a GPON Quad play architecture. Also, we found the best wavelength for quad play. Based on our experiment, we propose 1550 nm wavelength for GPON quad play for better performance.

Our main interest was to develop a quad play architecture with a MUX instead of EDFA and to find out the exact wavelength for GPON quad play. We have simulated several ways with several wavelength combinations and found the best performance at 1550 nm for voice, video and data.

6.2 Proposals for Future Work

The procedure for data transmission in GPON networks depends on the direction of the communications. Broadcast for downstream and full data rate are transmitted to all ONUs. In that case, each ONU filters the received data and only accepts its own traffic. The upstream channel uses Time Division Multiple Access (TDMA) where OLT controls the upward capacity assigning bandwidth for all users. Each ONU transmits in slot time windows, for avoiding collisions. It should use unicast or multicast to its downstream. In our future research project, we will work on how to omit broadcast or TDM of GPON downstream and establish unicast. By establishing unicast, network performance could increase. So, the following works can be carried out in future:

(i) Minimizing broadcast of GPON quad play.
(ii) Designing a DBA profile for GPON quad Play Service.
(iii) Analysing GPON Penta play possibility (Voice, Video, Data, SDH and Wi-Fi).

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Appendix

Various Parameter Calculation of DWDM network with an Example link:

Consider a DWDM link with two ROADM sites at transmitter and receiver ends with an intermediate pass-through ROADM as shown in Figure-3.5. ROADM sites at Tx and Rx are of degree 2 and pass-through ROADM had degree equal to 4. Link has two spans with fiber of type SMF having lengths L1 and L2. As mentioned earlier,

ROADMs are usually accompanied with Booster and Pre-amplifiers. B1 and B2 are Booster amplifiers whereas P1 and P2 are Pre-amplifiers. Input given to Mux is 0 dBm which is given form the transponder.

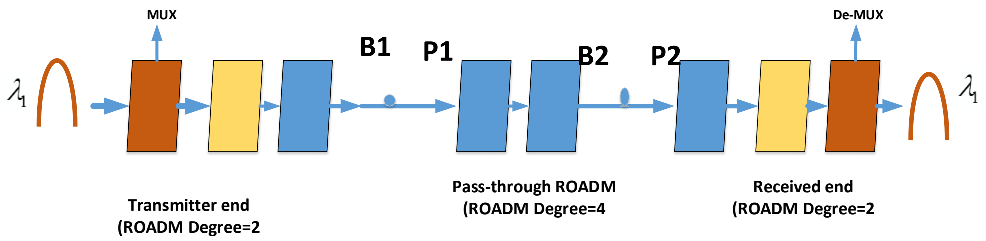

Figure-A-II: DWDM ROADM link example

Let L1 = 80 Km and L2 = 120 Km SMF fiber.

Fiber Attenuation loss = α x Length

L1 Loss = 0.257 dB/km x 80 km = 22 dB

L2 Loss = 0.275 dB/km x 120 km = 33 dB

3.5.1 Dispersion Compensation:

Dispersion = Length x Dispersion coefficient

L1 Dispersion = 80 Km x 17 ps/nm- km = 1360 ps/nm

L2 Dispersion = 120 Km x 17 ps/nm- km = 2040 ps/nm

Total Link Dispersion = 1360 ps/nm + 2040 ps/nm = 3440 ps/nm (> 1020 ps/nm)

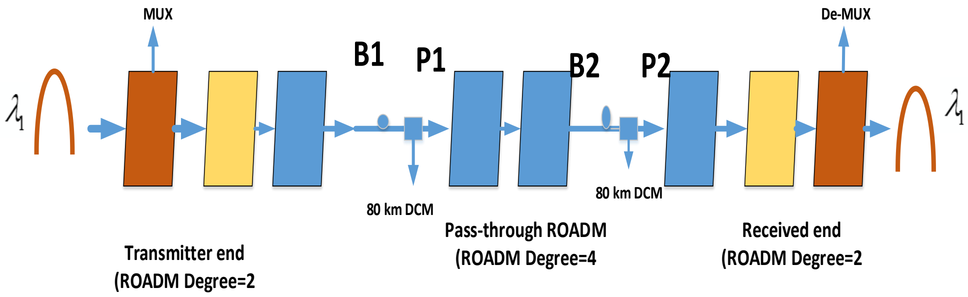

Figure-A-II: Example link with MUX and De-MUX

To compensate for this high dispersion of 3440 ps/nm, an 80 Km DCMs are placed at the end of L1 and. Figure-3.6 shows link with DCM placement at the end of L1 and L2. Therefore, the dispersion now with DCMs at the receiver node is;

Residual Dispersion = 3440 ps/nm – (2 x 80 km x 17ps/nm-km)

= 680 ps/nm (-510 ps/nm < 680 ps/nm < 1020 ps/nm)

EDFA Placement:

Placement of EDFA depends on the span loss. Maximum gain for an EDFA is 30 dB, i.e. to have an output power of 1 dBm per channel, minimum input power will be -29 dBm (-29 dBm + 30 dB = 1 dBm). Since B1, B2, P1 and P2 are all EDFAs, their outputs need to be maintained at 1 dBm / ch.

Gain calculation of B1:

B1 I/P power = (Pin1 – MDU Loss – D/L ROADM Loss – Degree ROADM Loss) = 0 – 14 – 4 – 4 = -22 dBm

Therefore, B1 Gain = 23 dB (15 dB < 23 dB < 30 dB)

Gain calculation of P1:

P1 I/P power = B1 O/P power – Span 1 Loss

Span 1 Loss = (L1 Loss + (2 x Connector Loss) + DCM Loss) = 22 + 1 + 4 = 27 dB

P1 I/P power = 1 – 27 = -26 dBm

Therefore, P1Gain = 27 dB (15 dB < 27 dB < 30 dB)

Gain calculation of B2:

B2 Input Power = (P1 O/P power – Degree ROADM 1 – Degree ROADM 2) = 1 – 7 – 9 = -15dBm

Therefore, B2 Gain = 16 dB (15 dB < 16 dB < 30 dB)

Gain calculation of P2:

P2 I/P power = B2 O/P power – Span 2 Loss

Span 2 Loss = L2 Loss + (2 x connector Loss) = 33 + 1 = 34 dBm

P2 I/P Power = 1 – 34 = -33 dBm

Therefore, P2 Gain = 34 dB (> 30 dB)

By observing the gain value needed for P1 EDFA, it becomes clear that power budget exceeds the limit and an extra line amplifier is necessary for second span of the link. Now it becomes important to decide at what point line amplifier has to be placed. Placement of amplifier must be such that-

• No more unnecessary line amplifiers must be needed further in the span, and

• OSNR value at the receiver must be good enough and within the limit.

Figure-3.7. represents second span of the DWDM link split into L11 and L22 on either sides of the Line Amplifier (LA) along with the 80 km DCM at the end of L22.

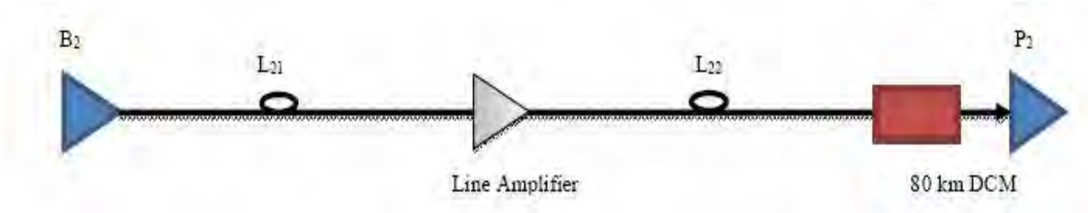

Figure-A-IV: Example link with Line Amplifier

Amplifier is placed at a point where minimum gain can be achieved i.e. 15 db. This implies; Line Amp O/P power = Gain – Span Loss (Line Amp) = 1dBm

If Gain = 15 dB, then Line Amp I/P power = 14 dBm

L_{21} Loss = (LA I/P power – (2 x Connector Loss) + B2 O/P power = 14 – 1 + 1 = 14 dB

Thus,

$L_{22} = L_2 - L_{21}$ = 120 – 50.9 = 69.1 km

Length $L_{21} = L_{21}$ Loss (dB) / α (dB/km) = 14 / 0.275 = 50.9 km

L_{22} Loss = 69.1 x 0.275 = 19 dB

Total span loss of $L_{22} = L_{22}$ Loss + DCM Loss + (2 x Connector Loss) = 19 + 4 + 1 = 24 dB

P2 I/P power = LA O/P power – Total Span Loss of L22 = 1 – 24 = -23 dBm

Thus, Gain of P2 = 24 dB (15dB < 24dB < 30dB)

After calculating I/P, O/P and gain power values for EDFA the last step remaining is calculating the input power at the receiving XFP connected to the De-Mux.

I/P to XFP = (P2 O/P power – Degree ROADM Loss – D/L ROADM Loss – MDU Loss)

= 1 – 7 – 7 – 7

= -20 dBm (> -25 dBm)

Loss and splitting ratio calculation of an example link:

An optical signal degrades as it propagates through a network. Components, such as fiber cables, splitters, and switches, introduce attenuation. The maximum allowable distance between a transmitting laser and receiver is based upon the optical link budget that remains after subtracting the power loss experienced by the signal as it transverses the components at each node. These losses are principally fiber loss, connector loss, and splitter loss. The degradation effect is also impacted by the wavelength used, e.g. 1310 nm vs. 1550 nm. Signal loss (or gain) within a system is expressed using the decibel (dB). dB is not a measure of signal strength, but, is a measure of signal power attenuation or gain. It is important not to confuse decibel and decibel milliwatt (dBm), as the latter is a measure of signal power relative to 1mW. Thus, a signal power of 0 dBm is 1mW, a signal power of 3dBm is 2mW, 6 dBm is 4 mW, and so on. The purpose in the calculation example below is to measure the optical loss in a system so as to determine the allowable split ratio of a new tap installation.

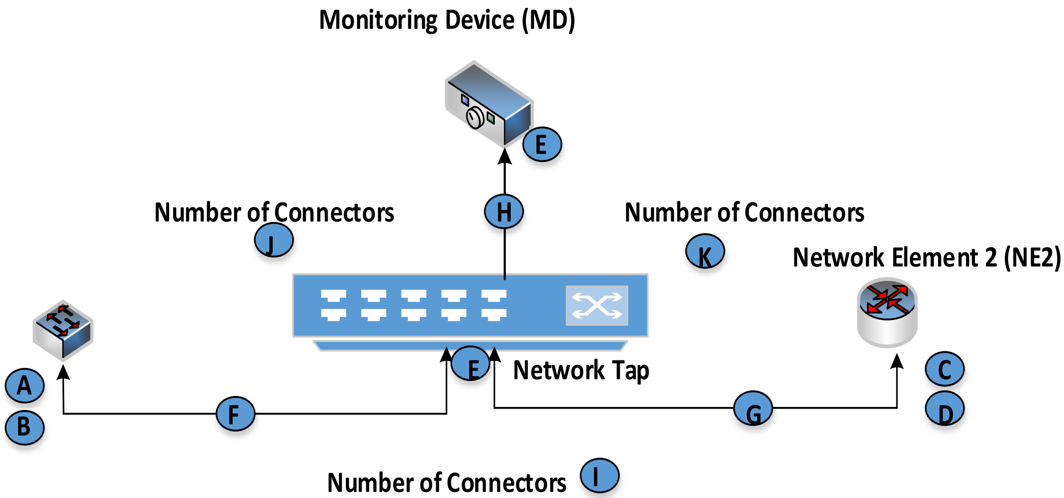

Figure-A-I: Example link for splitting Ratio

The calculations conducted are to verify that (Span budget) - (Fiber loss) - (Connector loss) is greater than (Splitter loss). In this example, the optical losses are calculated based on assumed conditions. The user should verify these conditions prior to selecting the tap's split ratio.

A: Network Element 1, Transmit Power (dBm) = -9.5 dBm

B: Network Element 1 (NE1), Receiver Sensitivity = -17 dBm

C: Network Element 2 (NE2), Transmit Power = -9.5 dBm

D: Network Element 2, Receiver Sensitivity = -17 dBm

E: VSS Optical Tap or Monitor Device, Receiver Sensitivity = -21 dBm

F: Distance between Network Element 1 and VSS Optical Tap = 0.9 km

G: Distance between VSS Optical Tap and Network Element 2 = 0.09 km

H: Distance between VSS Optical Tap and Monitoring Device = 0.002 km

I: Number of Connectors in the path between NE1 and Tap = 2

J: Number of Connectors in the path between NE2 and Tap = 4

K: Number of Connectors in the path between Tap and MD = 2

L: Split Ratio in tap = 70:30 Standard

- Split Loss in tap for Network < 2.5 dB (70%)
- Split Loss in tap for Monitor < 6.3 dB (30%)

Wavelength used is 1310 nm.

Step 1: Consider path NE1 to NE2

The NE1 to NE2 path is important for passive optical splitters between the two network ports on the tap.

Need to calculate for both directions.

NE1 to NE2:

=> (A - D) - 3 * (F + G) - 0.5 * (I + J)

=> (-9.5 - (-17)) - 3 * (0.9 + 0.09) - 0.5 * (4 + 2)

=> 7.5 - 2.97 – 3

Assuming 70% splitter loss =< 1.9 dB

=> 3.53 > 1.9

NE2 to NE1:

=> (C - B) - 0.4 * (F + G) - 0.2 * (I + J)

=> (-9.5 - (-17)) - 0.4 * (0.9 + 0.09) - 0.2 * (4 +2)

=> 7.5 - 0.396 - 1.2Assuming 70% splitter loss =< 1.9 dB

=> 5.904 > 1.9

So, 70:30 split ratio is OK.

Step 2: Consider path NE1/NE2 to Monitoring Device

The NE to MD paths are only important for completely passive optical taps.

Need to calculate for each NE.

NE1 to MD:

=> (A - E) - 0.4 * (F + H) - 0.2 * (I + K)

=> (-9.5 - (-21)) - 0.4 * (0.9 + 0.002) - 0.2 * (4 +2)

=> 11.5 - 0.3608 - 1.2

Assuming 30% splitter loss is =< 5.7 dB

=> 9.9392 > 5.7

NE2 to MD:

=> (C - E) - 0.4 * (H + G)) - 0.2 * (J + K)

=> (-9.5 - (-21)) - 0.4 * (0.09 + 0.002) - 0.2 * (2 + 2)

=> 11.5 - 0.0368 - 0.8

Assuming 30% splitter loss is =< 5.7 dB

=> 10.6632 > 5.7

So, 70:30 split ratio is OK.

Step 3: Consider path NE1/NE2 to Tap

The NE to Tap paths are important for taps that terminate the split signal internally and then regenerate the signal to the monitor ports and/or other network ports. It is not required for completely passive optical taps.

Need to calculate for each NE.

NE1 to TAP:

=> (A - E) - (0.4* F) - (0.2 * I)

=> (-9.5 - (-21)) - (0.4 * 0.9) - (0.2 * 4)

=> 11.5 - 0.36 - 0.8

Assuming 30% splitter loss is =< 5.7 dB

=> 10.84 > 5.7

NE2 to TAP:

=> (C - E) - (0.4*G) - (0.2 * I)

=> (-9.5 - (-21)) - (0.4 * 0.9) - (0.2 * 2)

=> 11.5 - 0.36 - 0.4

Assuming 30% splitter loss is =< 5.7 dB

=> 10.74 > 5.7

So, 70:30 split ratio is OK.

Outcome of this Research Work

1. Md. Hayder Ali and Md. Saiful Islam, **"GPON as a Solution of Bandwidth Sharing for Triple Play with High Performance and Low Cost".** 10th Global Engineering, Science and Technology Conference, January, 2015, BIAM Foundation, Dhaka, Bangladesh, ISBN: 978-1-922069-69-6.

2. Md. Hayder Ali and Md. Saiful Islam, "**Design, Develop and Cost analysis of GPON Triple Play Architecture without EDFA Combiner for fixed Wave Length with High Performance."** 5th International Conference on Informatics, Electronics & Vision (ICIEV-2016), 13-14 May, 2016, University of Dhaka, Bangladesh.

3. Md. Hayder Ali and Md. Saiful Islam, "**GPON Triple Play and SDH Connectivity Structure with Cost Analysis."** 1st International Conference on Advanced Information and Communication Technology 2016 (ICAICT-2016), May 16-17, 2016, Chittagong Independent University, Chittagong, Bangladesh.

MATLAB Code:

```
% BER vs Received power curve
clc;
clear;
R=0.8;
R1=(1-R)/R;
R2=sqrt(R*(1-R));
Rd=0.8;
B=2.5e9;
k=1.38e-23;
T=300;
RL=50;
q=1.6e-19;
sigma_thermal_s=2 * k * T / RL * B;
sigma_0_s=sigma_thermal_s;
sigma_0=sqrt(sigma_0_s);
p1_dBm=-2;
p1=10^(p1_dBm/10)*1e-3;
i=0;

for pi_dBm=-35:1:-6
i=i+1;
pi=10^(pi_dBm/10)*1e-3;
E=pi/p1;
Pr1=0.9*R*p1+(1-R)*p1*E-2*R2*p1*sqrt(E);
I1=Rd*Pr1;
Rp1(i)=10 * log(Pr1*1e3);
sigma_shot_s=q * B * I1;
sigma_1_s=sigma_shot_s + sigma_thermal_s;
sigma_rin_s=R1*E;
BER1(i)=0.25 * erfc(0.353 * I1/(sqrt(sigma_1_s + sigma_rin_s *
I1^2 ))) + 0.25 * erfc(0.353 * I1/sigma_0);

Pr2=1.17*R*p1+2*(1-R)*p1*E-2*2*R2*p1*sqrt(E);
I2=Rd*Pr2;
Rp2(i)=10 * log(Pr2*1e3);
sigma_shot_s=q * B * I2;
sigma_1_s=sigma_shot_s + sigma_thermal_s;
sigma_rin_s=R1*2*E;
BER2(i)=0.25 * erfc(0.353 * I2/(sqrt(sigma_1_s + sigma_rin_s *
I2^2 ))) + 0.25 * erfc(0.353 * I2/sigma_0);

Pr3=1.45*R*p1+3*(1-R)*p1*E-2*3*R2*p1*sqrt(E);
```

```
I3=Rd*Pr3;
Rp3(i)=10 * log(Pr3*1e3);
sigma_shot_s=q * B * I3;
sigma_1_s=sigma_shot_s + sigma_thermal_s;
sigma_rin_s=R1*3*E;
BER3(i)=0.25 * erfc(0.353 * I3/(sqrt(sigma_1_s + sigma_rin_s *
I3^2 ))) + 0.25 * erfc(0.353 * I3/sigma_0);
end
format long;
semilogy(Rp1, BER1,'r-*');
hold on;
semilogy(Rp2, BER2,'g-o');
semilogy(Rp3, BER3,'b-+');
axis([-15 2 1e-7 1e-0]);
grid on;

legend('n=3','n=2','n=1')

xlabel('Receive Power(dBm)');
ylabel('Bit Error Rate');


% Power Penalty Vs Crosstalk

clc;
clear;
R=0.62;
R1=(1-R)/R;
R2=sqrt(R1);
R3=(1-R)^2/R;
R4=sqrt(R3);
p1_dB=-15;
p1=10^(p1_dB/10);
p2_dBm=-20;
p2=10^(p2_dBm/10)*1e-3;
i=0:1:20;
E=p2/p1;
cros1=10*log10((1-R)*i*p2*1e-3);

cros2=10*log10((1-R)^2*i*p2*1e-3);


plot(i,cros1,'r-o');
hold on;
plot(i,cros2,'g-*');
%plot(cros31,pp31,'k-*');
axis([0 20 -84 -68]);
legend('CWDM','DWDM')
```

```
xlabel('Number of Channel');
ylabel('Crosstalk (dB)');


% Power Penalty Vs Crosstalk

clc;
clear;
R=0.8;
R1=(1-R)^2/R;
R2=sqrt(R1);
p1_dB=-11.9;
p1=10^(p1_dB/10);
i=0;
%for E=0.0000001:0.000001:0.001
for p2_dBm=-40:1:-1
i=i+1;
p2=10^(p2_dBm/10)*1e-3;
E=p2/p1;
pp11(i)=-10*log10(1-R2*20*sqrt(E));
cros11(i)=10*log10((1-R)^2*20*p2*1e-3);
pp21(i)=-10*log10(1-R2*40*sqrt(E));
cros21(i)=10*log10((1-R)^2*40*p2*1e-3);
pp31(i)=-10*log10(1-R2*60*sqrt(E));
cros31(i)=10*log10((1-R)^2*60*p2*1e-3);
end
plot(cros11,pp11,'g-o');
hold on;
plot(cros21,pp21,'b-.');
plot(cros31,pp31,'r-*');
axis([-100 -40 0 3]);
legend('n=10','n=15','n=20')

xlabel('Crosstalk(dB)');
ylabel('Power penalty(dB)');


% Relative Intensity Noise Vs Power Penalty

clc;
clear;
R=0.8;
R1=(1-R)^2/R;
R2=sqrt(R1);
p1_dB=-21.2;
p1=10^(p1_dB/10);
```

```
i=0;
for p2_dBm=-50:1:-2
i=i+1;
p2=10^(p2_dBm/10)*1e-3;
E=p2/p1;
pp1(i)=-10*log10(1-R2*10*sqrt(E));
rin1(i)=10*log10(R1*10*E);
pp2(i)=-10*log10(1-R2*15*sqrt(E));
rin2(i)=10*log10(R1*15*E);
pp3(i)=-10*log10(1-R2*20*sqrt(E));
rin3(i)=10*log10(R1*20*E);
end
plot(rin1,pp1,'g-o');
hold on;
plot(rin2,pp2,'b-.');
plot(rin3,pp3,'r-*');
axis([-45 -5 0 4.5]);
%plot(cros1,pp1);
%plot(cros2,pp2);
%plot(cros3,pp3);
legend('n=10','n=15','n=20')

xlabel('Relative Intensity Noise(dB)');
ylabel('Power penalty(dB)');


% Plot of Relative Intensity Noise Vs Number of channel

clc;
clear;
R=0.8;
R1=(1-R)/R;
R2=(1-R)^2/R;
i=0:1:20;
E=10^(-27/10); %pi/p1;
RIN1=R1.* i * E;
RIN2=R2.* i * E;
plot(i,RIN1,'r-o')
hold on;
plot(i,RIN2,'b-*')
axis([0 20 0 0.02]);
grid on;
legend('DWDM','CWDM')
xlabel('Number of Channel)');
ylabel('Relative Intensity Noise (mw)');
```

```
% Crosstalk vs Wavelength

clc;
clear;
clear all;
lambda_bragg=1550*1e-9;
new= 0.80;
del_eff=1.55*1e-4;
%length=1e-2;
eff=1.46;
lambda= 1549.70:0.001:1550.30;
%for L=1:3:8
length=5e-2;
kappa=(pi*del_eff*new)/lambda_bragg;
sigma_bar=2*pi*eff*(1./(lambda*1e-9)-1/lambda_bragg);
delta=2*pi*eff*(1./(lambda*1e-9)-1/lambda_bragg);
del_len=delta*length;
gamma=sqrt(kappa.^2-sigma_bar.^2);
R= (((sinh(gamma*length)).^2)./((cosh(gamma*length)).^2-
sigma_bar.^2/kappa.^2));
p1_dB=-1;
pn_dB=-27;
p1=10^(p1_dB/10);
pn=10^(pn_dB/10);
E=pn/p1;
cross2=10*log10((1-R).^2*p1*E);
plot(lambda, cross2,'g-');
axis([ 1549.7 1550.3 -250 0]);
xlabel('Wavelength(nm)');
ylabel('Crosstalk(dB)');
```