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# Study of Bidirectional Broadband Passive Optical Network (BPON) Using EDFA

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# STUDY OF BIDIRECTIONAL BROADBAND PASSIVE OPTICAL NETWORK (BPON) USING EDFA

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**Abstract**

Optical line terminals (OLTs) and number of optical network units (ONUs) are two main parts of passive optical network (PON). OLT is placed at the central office of the service providers, the ONUs are located near to the end subscribers. When compared with point-to-point design, a PON decreases the number of fiber used and central office components required.

Broadband PON (BPON), which is one type of PON, can support high-speed voice, data and video services to subscribers' residential homes and small businesses. In this research, by using erbium doped fiber amplifier (EDFA), the performance of bi-directional BPON is experimented and tested for both downstream and upstream traffic directions. Ethernet PON (E-PON) and gigabit PON (G-PON) are the two other kinds of passive optical network besides BPON. The most beneficial factor of using BPON is it's reduced cost. The cost of the maintenance between the central office and the users' side is suitable because of the use of passive components, such as a splitter in the BPON architecture.

In this work, a bidirectional BPON has been analyzed for both downstream and upstream cases by using bit error rate analyzer (BER). BER analyzers test three factors that are the maximum Q factor, minimum bit error rate, and eye height. In other words, parameters such as maximum Q factor, minimum bit error rate, and eye height can be analyzed utilized a BER tester. Passive optical components such as a splitter, optical

circulator, and filters have been used in modeling and simulations. A 12th edition Optiwave simulator has been used in order to analyze the bidirectional BPON system. The system has been tested under several conditions such as changing the fiber length, extinction ratio, dispersion, and coding technique. When a long optical fiber above 40km was used, an EDFA was used in order to improve the quality of the signal.

**Acknowledgment**

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I am so grateful to my parents. I could not finish this masters program without their full support. Finally, I would like to give a special thanks to my wife. I am grateful to her for her love and understanding throughout all my endeavors all through my masters.

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## List of Acronyms

| | |
|---|---|
| AES | “Advanced Encryption Standard” |
| AON | “Active Optical Network” |
| APD | “Avalanche Photo Diode” |
| APON | “Asynchronous Transfer Mode Passive Optical Network” |
| ATM | “Asynchronous Transfer Mode” |
| BER | “Bit Error Rate” |
| BPON | “Broadband Passive Optical Network” |
| CATV | “Cable Television” |
| DBA | “Dynamic Bandwidth Allocation” |
| DSL | “Digital Subscriber Line” |
| EDFA | “Erbium Doped Fiber Amplifier” |
| EFMA | “Ethernet in the First Mile Alliance” |
| EPON | “Ethernet Passive Optical Network” |
| FSAN | “Full-Service Access Network” |
| FTTB | “Fiber To The Building” |
| FTTC | “Fiber To The Curb” |
| FTTCab | “Fiber To The Cabinet” |
| FTTH | “Fiber To The Home” |

| | |
|---|---|
| FTTP | “Fiber-To-The-Premises” |
| FTTX | “Fiber-To-The-X” |
| 10GEPON | “10 Gigabit Ethernet Passive Optical Network” |
| GFP | “Generic Framing Procedure” |
| GPON | “Gigabit Passive Optical Network” |
| HDTV | “High Definition Television” |
| HFC | “Hybrid Fiber Coax” |
| IEEE | “Institute of Electrical and Electronics Engineers” |
| ITU-T | “ITU Telecommunication Standardization Sector” |
| LASER | “Light Amplification by Stimulated Emission of Radiation” |
| LED | “Light Emitting Diode” |
| MAC | “Media Access Control” |
| NT | “Network Termination” |
| OLT | “Optical Line Termination” |
| ONT | “Optical Network Termination” |
| ONU | “Optical Network Unit” |
| P2MP | “Point-to-Multi-Point” |
| P2P | “Point-to-Point” |
| PON | “Passive Optical Network” |

| | |
|---|---|
| POTS | “Plain Old Telephone Service” |
| QAM | “Quadrature Amplitude Modulation” |
| QoS | “Quality of Service” |
| QPSK | “Quadrature Phase-Shift Keying” |
| RN | “Remote Node” |
| SNI | “Service Network Interface” |
| SNR | “Signal-to-Noise Ratio” |
| SOA | “Semiconductor Optical Amplifier” |
| TDD | “Time Division Duplex” |
| TDMA | “Time Division Multiplexed Access” |
| TDM-PON | “Time Division Multiplexing Passive Optical Network” |
| UNI | “User Network Interface” |
| VDSL | “Very-High-Bit-Rate DSL” |
| WAN | “Wide Area Network” |
| WDD | “Wavelength Division Duplex” |
| WDM | “Wavelength Division Multiplexing” |
| WWW | “World Wide Web” |

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## Chapter One: Introduction

An optical fiber communication transmits information from one place to another using light as a carrier. In the 1970's, the cable was more popular than the optical fiber because of its very high attenuation. However, some scientists were able to reduce the attenuation of the optical fiber to only 0.2dB/km. Huge communication capacity, resistance to electromagnetic interference, and low transmission loss are three advantages can be offered by fiber optics [*1*]. The access network connects the service providers, which are the central office and the users such as residential homes. The need for the bandwidth has been aggressively increasing over the past years [*1*]. Significant increases from 35% to 40% in the quantity of subscribers that are online have been noticed by market research after upgrading the broadband connection [*2*]. Not only have the numbers of the subscribers increased, but the voice service has witnessed an increase of 8% to 9% per annum as well, eventhough the voice service used to be requested in small amounts [*2*]. Therefore, new technology, fiber-to-the-home (FTTH), has been produced to face this excessive increase. FTTH uses many implementations, but a PON implementation is the most suitable [*3*].

### 1.1 History of PON and Broadband Access Network

The last-mile networks term has been used in the past years for access networks since they include the last segment connection from central office to the end subscribers' side. Furthermore, they are named first- mile networks traditionally since they are the initial segment of the wider network observed by subscribers of telecommunication services [*4*]. Examples of access networks are twisted copper pairs linking to each residential home(also called local loops) and domestic coaxial cable falls from community antenna TV service suppliers. The type of access technique that utilizes radio waves for last-mile connection is called Wi-Max [*4*]. In the past years, because of backbone networks' large bandwidth and quite small losses, optical fibers have been commonly utilized in them. Optical fibers are have not been widely used as the last mile connection until the start of this century, even though fiber has been advertised for a long period of time [*4*].

Telecommunication networks created over the past years were industrialized for analog services. For years, 4kHz was the bandwidth needed in order to link to end subscribers for voice service. In industrialized countries, telephone companies have deployed a universal twisted copper network [*4*]. Assuming that such networks were enhanced for analog frequency transmission is not difficult. Actually, inductors known as loading coils have been settled in many old twisted copper pair plants to improve the voice frequency band performance in order to accomplish better economy and permit longer local loop drops [*4*]. On the other hand, loading coils significantly weaken high frequency signals outside the voice frequency band and make them inappropriate for broadband DSL services [*4*].

In the 1960s, the Internet was created [*4*]. For many years after its creation, the Internet was utilized by academia and research in order to share information. E-mail was the first popular application that is being used to this day. It was created in the early 1970s. The World Wide Web and its graphical user interface MOSAIC were invented in the early 1990s [*4*]. From that point on, the Internet became one of the most essential items in peoples' lives [*4*].

### 1.1.1 Digital Subscriber Line (DSL)

Digital subscriber lines and cable modem networks are the two main widely utilized access solutions. However, they cannot deliver enough bandwidth for services such as two-way video conferencing, video-on-demand, or interactive gaming [*5*]. DSL utilizes the same twisted pair as telephone lines and needs a DSL modem at the customers' properties and a digital subscriber in the CO [*5*]. The main principle of the technique is to split the spectrum of the line to a number of areas with the lower 4kHz being utilized by a plain old telephone service (POTS) apparatus, while the higher frequencies are assigned for higher-speed digital communication [*5*]. 1.5Mb/s bandwidth can be delivered in the downstream direction and 128kb/s bandwidth can be delivered in the upstream direction by using DSL [*5*]. The price of access technologies remains excessively high for the average residential homes while economies of scale have effectively allowed networks to develop quickly.

Furthermore, because of signal distortions, DSL has a limitation of 18,000 feet between the central office and the subscribers' properties side [*5*]. Typically, DSL suppliers do not offer services to subscribers if their location distance is more than 12,000 feet [*5*]. Even if the subscribers were ready to pay for the DSL service, an estimated percentage of 60% of the residential subscriber base in the upstream direction can use it [*5*].

Technologies such as very-high-bit-rate DSL (VDSL), which can support up to 50Mp/s bandwidth in the downstream direction, have even more distance limitations than DSL, although variations of VDSL are gradually developing [*5*]. For instance, the maximum VDSL capability of transmission is limited to 1,500 feet [*5*].

### 1.1.2 Cable TV

Cable television (CATV) is another substitute for broadband access network. Old CATV networks were a one-way distribution system. CATV networks were designed to transport analog distribution TV signals towards several TV subscribers [*4*]. Therefore, the CATV networks implemented a tree topology and assigned most of its spectrum for downstream analog channels. CATV is designed to have fibers connecting a video head end to a curbside optical node such as a hybrid fiber coax (HFC), and the final drop to the user being coaxial cable [*5*].

By integrating data services through cable television companies' HFC cable networks, a competition was created between and the telecommunications providers in delivering Internet service. This integration is needed to change downstream direction amplifiers utilized for analog video to bidirectional amplifiers, allowing an upstream traffic direction. Furthermore, the media was required to be deployed with a medium access protocol that prevents collision of upstream traffic sent by the subscribers [*5*]. The main limitation of CATV structure is that it is constructed in order to transmit podcast services. Therefore, they are not appropriate for distributing access bandwidth. 400MHz and 300MHz bands are allocated for downstream analog signals and downstream signals respectively out of a total cable spectrum width of approximately 740MHz [*5*]. In the upstream direction, 40MHz is left for 36Mb/s of information per optical node [*5*]. The performance of the network is frequently low and cannot meet the subscribers' expectations at the case of high load.

## 1.2 Overview of Access Network

Data, voice, or video services can be transmitted by using an access network over copper cables, optical fiber, wireless links, or usually a combination of copper and fiber. According to the application, the components between the last mile and the feeder can be either passive or active [*6*]. The data rate transmitted differs from one access network technology to another. WiMax could offer 70Mbit/s connection for a distance of 5km [*6*]. On the other hand, WiFi could offer 50Mbit/s connection for a distance up to 100 meters [*6*]. Digital subscriber line (DSL) is able to offer point-to-point access wire line technology to help each subscriber with up to 24Mbit/s [*6*]. Nevertheless, the effective bandwidth for each subscriber is limited depending on the local loop length because of huge noise limitations, particularly at high frequency. For instance, the local loop length has to be reduced to around 1km in order to admit subscribers to accept compelling Internet and video services at 30Mbit/s in the downstream with 1Mbit/s upstream ability [*6*]. As shown in Table 1.1, the recommended downstream in order to offer triple-play services for a distinct residential user is 73Mbit/s, containing three high-definition television (HDTV) channels (3*20 Mbit/s), high-speed Internet access (10Mbit/s), video-structure (2Mbit/s), and telemetric/remote control (1Mbit/s) [*6*].

In upstream traffic direction, services such as video-conferencing, video gaming and other services are estimated to require up to 53Mbit/s bandwidth [*6*]. In the near future, the needed symmetrical bandwidth for a distinct residential user or small business is anticipated to grow up to 100Mbit/s by adding services such as remote backup and Web 2.0 applications [*6*].

| Service | Bandwidth | Type and Requirement |
|---|---|---|
| Three HDTV channels per residential at 20Mbit/s each | 60Mbit/s | Three HDTV channels |
| Education-on-demand, online gaming, Internet | 10Mbit/s | Peer-to-peer require symmetrical bandwidth |
| Video conference of video phone | 2Mbit/s | Requires symmetrical bandwidth |
| Remote control and sensing | 1Mbit/s | Requires symmetrical bandwidth |
| Overall | 73Mbit/s | Downstream: 73Mbit/s<br>Upstream: 53Mbit/s |

Table 1.1: Approximate bandwidth on behalf of a single residential user [*6*]

### 1.3 Development of Fiber Optic Systems

With all of this progress and growth in the communication system area, there is an excessive demand for large bandwidth to transmit more data at higher speed [*7*]. Residential users need high-speed network for data, voice, or video services. This demand requires the networks to be with higher capacities at a lower cost. One of the main developments in the communication system area is progressing from the copper wire that was used in the past to the fiber optic cable that is used today [*7*]. This development increased the ability to transmit more data at a higher speed and over longer distances. By using fiber optic cables, higher bandwidths can be transmitted. Huge transmission capacity at longer distances can be accomplished by developing the optical networks [*7*]. Some factors such as fast and efficient wavelength conversion, multiplexing, de-multiplexing, optical combining and optical splitting have to be achieved in order to transmit higher data rates [*7*].

### 1.3.1 Optical Amplifiers

In optical fiber communication, when the signal is desired to be transmitted to a long transmission distance, there will be degradation. To overcome that drawback in the optical fiber, optical amplifiers are used [*6*]. They are designed to amplify the transmitted optical signal without converting the signal into the electrical form. In linear mode, the optical amplifiers are used as repeaters. However, in nonlinear mode, the optical amplifiers are used as optical gates, routing switches, and pulse sharpers. In WDM light wave system, the optical amplifiers are used to amplify all the channels at the same time and that process can be named as optical in-line amplifiers [*6*]. The optical amplifiers are also able to amplify signals at different wavelengths at the same time. Power booster can be created on the optical amplifier that increases the transmitted power by installing the optical amplifier immediately after the transmitter [*6*]. On the other hand, optical pre-amplifier can be created on the optical amplifier that increases the received power and increases the transmission distance by installing the optical amplifier just before the signal reaches the receiver [*6*].

## 1.4 Optical Network

If a signal is desired to be transmitted from one place to another, some kind of signal path is required. In order to generate this kind of path, a medium is needed to transmit the data [*8*]. The medium itself depends on the application and the infrastructure available. Copper cables, air, and optical fibers are some examples of mediums that can be used. By using this media, electrical networks, radio networks, and optical networks can be designed and used.

In this proposed research, optical fiber is the media that has been used in order to design an optical network [*8*]. Three essential components are required in the optical network: lasers, fiber and detectors. A transceiver can be designed by combining a laser and a detector, which are able to convert an electrical signal to an optical signal and an optical signal to an electrical signal [*8*].

Optical networks are similar to electrical networks. Optical networks are designed with the help of switching and routing components. Depending on the type of these switching and routing components, optical networks can be configured in different ways [*8*]. Two main examples of optical network configurations are active and passive configuration. Active optical network configuration is built with switches and routers, which have their own power, supply. On the other hand, passive optical network configuration is built with switches and routers, which do not have their own external power, supply [*8*].

### 1.4.1 Point-to-Point Architecture

As can be seen from the name, in this architecture, single optical fiber runs the OLT in the OC to its corresponding ONU [*7*]. Otherwise, the optical fiber runs to each home. That is often referred to as a “home-run fiber” [*7*]. The architecture for the P2P is demonstrated in Figure 1.1. A separate optical fiber is laid from the OLT to the ONU as can be shown in the figure.

As P2P architecture has its own advantages, it has disadvantages as well. One main advantage is the capability to deliver the extreme capacity, and fully gratify each user’s needs [*7*]. Higher flexibility in delivering services to users can also be satisfied when single optical fiber pair is used. However, there are some main disadvantages of using P2P architecture. At the OLT in the CO side, the demand for core components should be balanced with the number of ONUs [*7*]. These components might cause trouble in connection with space and power consumption besides the cost of the achievement. P2P demands a large number of optical fiber pairs, which needs installation and maintenance [*7*].

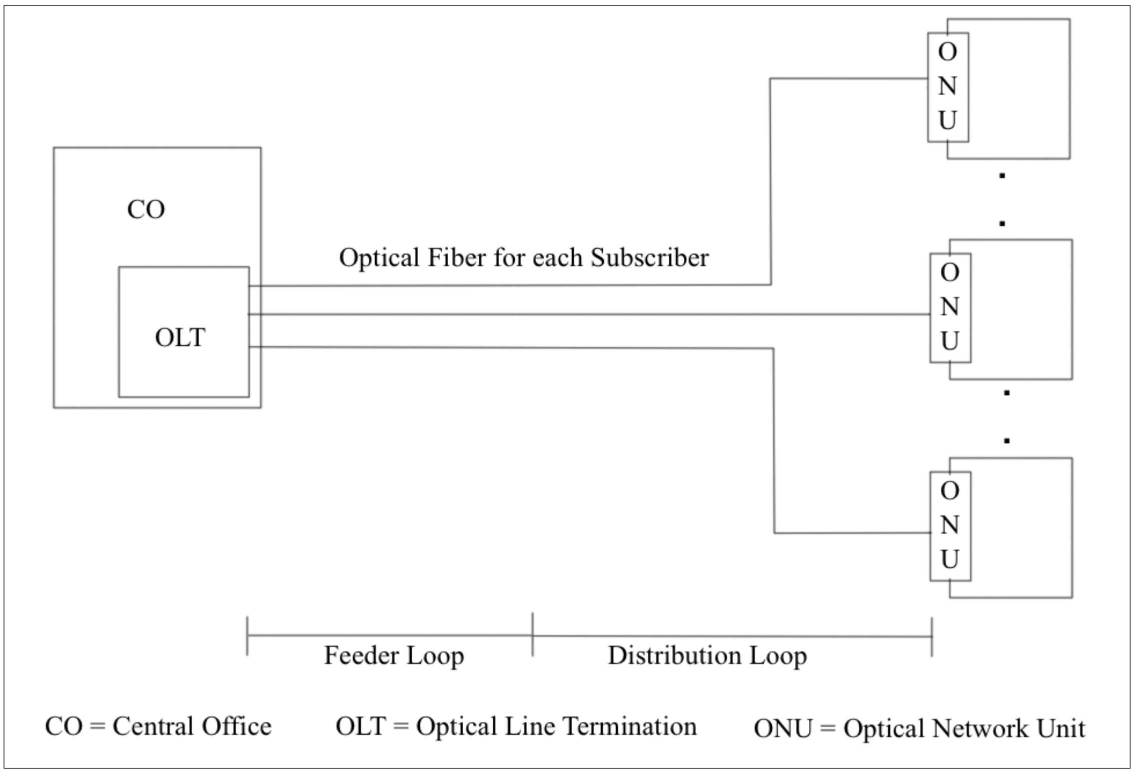



Figure 1.1: P2P architecture

### 1.4.2 Active Optical Network

AON is designed to have a distinct optical fiber feeder that carries all the traffic to the RN close to the users side from the CO. It is commonly referred to as the Active Ethernet Network, because desired components provide TV, telephone and Internet connections through a common Ethernet standard [*7*]. Active components are located in the RN. The function of the active components is to handle the data frames that are transmitted from the OLT in the CO to the RN, and deliver just frames to their corresponding ONU in the users side [*7*]. Single optical fibers are distributed to their destinations, such as cabinet/curb, home, or building from the RN to ONUs, depending on the application that is applied as shown in Figure 1.2.

The major advantage of the AON architecture compared with P2P architecture is that it uses an individual shared fiber to deal with a specific area, thus reducing the number of optical fibers as well as the cost of the whole structure. Also, AON scales better than the P2P configuration [*7*].

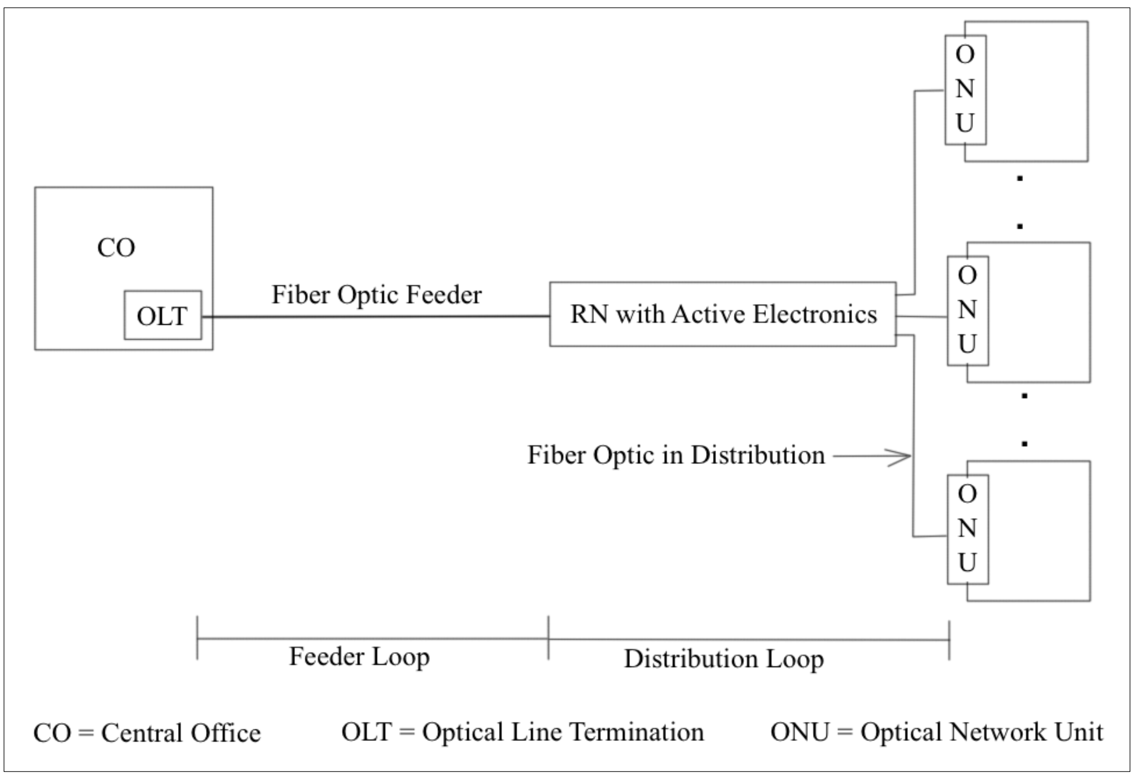



Figure 1.2: AON architecture

### 1.4.3 Passive Optical Network

In PON architecture, the RN with the active components in it in the AON architecture is replaced with a passive optical power splitter as can be seen in

Figure 1.3. The optical splitter is denoted as a passive component because it does not require any power and its function is just to distribute all the data it receives to its corresponding ONU [*7*]. The task of ONU in the PON architecture is to sort out the exact packet that belongs to each subscriber. Because the OLT element is very essential in the PON architecture, it can be considered the “brain” of a PON network. This is because it performs very important tasks such as buffer control, traffic scheduling, and bandwidth allocation [*7*]. In PON architecture, ONUs are usually more expensive than in the AON architecture because they perform additional data processing tasks [*7*].

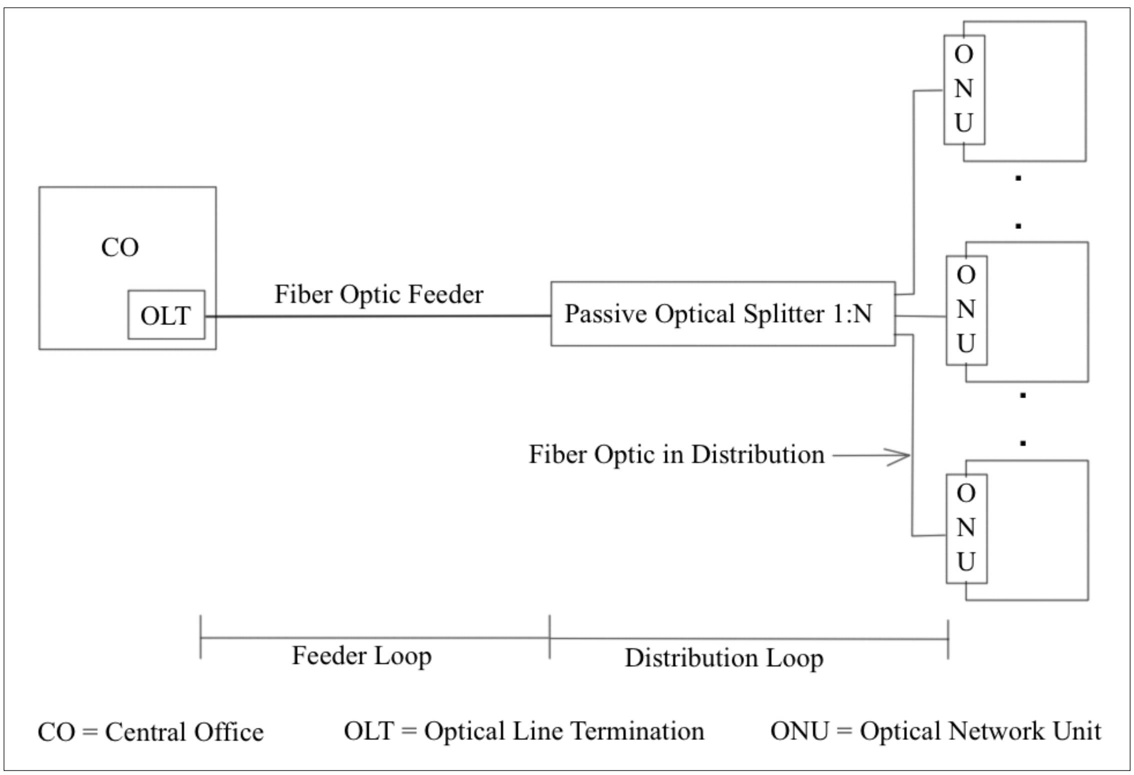



Figure 1.3: PON architecture

### 1.5 Fiber Dispersion

Pulse widening resulting in increasing the interference between adjacent sent symbols can be produced by dispersion in optical fiber [*9*]. Therefore, there will be high chance of having ‘1’ state instead of ‘0’ state and ‘0’ state instead of having ‘1’ state, and thus the bit error rate of the system will increase. In optical fiber, dispersion results from different mechanisms. The dominant mechanism is inter-model dispersion for multimode fiber [*9*]. The different group velocities of the propagation modes of the optical fiber produce the inter-model dispersion [*9*].

The inter-model dispersion is excluded in the single mode fiber because it has only one propagation mode [*9*]. Polarization mode dispersion, material dispersion, and waveguide dispersion are three main dispersion mechanisms that could happen in the single mode fiber [*9*]. In communication systems, a transmitted message has either a band or group of frequencies. Group velocity is the velocity of this group frequency [*9*]. Group velocity dispersion can be produced when having group velocity as a function of wavelength [*9*].

When comparing polarization mode dispersion (PMD) with material and waveguide dispersion, it can be seen that PMD is smaller. PMD was disregarded for practical transmission before the year 2000, and thus most of the fiber inserted in the transmission system before this year did not have a PMD specification [*9*]. Material and waveguide dispersion are static properties of the optical fiber and can be compensated by utilizing dispersion compensation components such as dispersion compensation fiber [*9*]. PMD is different from material and waveguide dispersion, because it is dependent on the physical environment the fiber is facing, and this changes as a result of environmental factors such as temperature and pressure. PMD is time varying [*9*].

### 1.6 Problem Statement

The optical bidirectional BPON transmission has its own advantages. Higher rate transmission can be possible in BPON when optical amplifiers such as semiconductor optical amplifiers (SOA), erbium doped fiber amplifiers (EDFA), hybrids, or Ramans are used. In this proposed research, EDFA has been used because of its low affective cost. After using this kind of amplifier, the performance of the signal in the customer side has been examined by using a BER analyzer. The examination includes parameters, such as maximum Q factor, minimum BER, eye height, extinction ratio, and dispersion.

### 1.7 Scope of The Research

The scope of this work is to study the performance of a BPON design. BPON is a derivate of APON or ATM based networks. BPON has the capability of supporting high-speed data, video services and voice services to subscribers' homes and small businesses. BPON has the ability to deliver high-speed access with recognized technology with new implementations because of installed ATM and SONET systems. An optical amplifier has been installed in order to increase the performance of the transmitted signals to further distances. A BER analyzer has been used to study the performance of the sent signal in different situation conditions such as fiber length, type of the coding technique used, number of users, and others.

### 1.8 Methodology

In the 12th version of the Opti-system, an optical communication software has been used to simulate the BPON system. The Opti-system program offers the ability to use the optical components it provides in order to build the optical design. It is a creative optical communication system simulator that tests and optimizes any type of optical link. The BER analyzer has been used to analyze the performance of the designed system under different situations.

# Chapter Two: Passive Optical Network (PON)

PON, as can be noticed from the name, depends mostly on passive components from the central office to the users side. Passive component means it does not need power to operate. In PON, the traffic signals are directed within a specific range of wavelengths to the users. The return back to the central office can then be done by using passive optical components [*10*]. PON, which is an optical connection, can transmit much more bandwidth in comparison to the coaxial cable. Because PON uses passive components, it requires low maintenance prices. PON provides high bandwidth and offers a large coverage area as well [*1*]. PON consists of some essential components such as optical line terminals (OLT), remote node (RN), and optical network units (ONUs). OLT is located in the central office, RN contains couplers and splitters to multiplex and de-multiplex the downstream and upstream traffic, and ONUs receive the downstream traffic from the RN and give it the upstream traffic [*1*].

## 2.1 Passive Optical Network Architecture

A PON is made up of three major parts as shown in Figure 2.1. A head end expresses the OLT in the service providers' side and ONU in the users side [*8*]. The OLT and ONU are connected together by an optical splitter.

As can be seen in Figure 2.2, a simple model of a standard fundamental PON is presented. The PON connects switching equipment in the central office with many users by optical fibers [*10*]. By using a wavelength of 1490 nm, digitized data and voice are packed in the central office and transmitted downstream to subscribers through optical fiber. Upstream direction, which runs from the subscribers to the central office, utilizes a wavelength of 1310 [*10*]. A wavelength of 1550 nm is required when video services are wanted to be transmitted [*11*]. However, the video services can only be transmitted in the downstream direction [*10*]. The figure shows that all the subscribers use a wavelength of 1310 nm in the upstream direction. Therefore, in order to avoid interference, timing is required. The process of bidirectional PON starts from the central office and ends in the central office because it has downstream and upstream directions traffic [*10*]. One individual optical fiber feeder runs to the passive optical splitter. The purpose of the passive optical splitter is to divide the power into several paths. Each path goes to its specified subscriber [*10*].

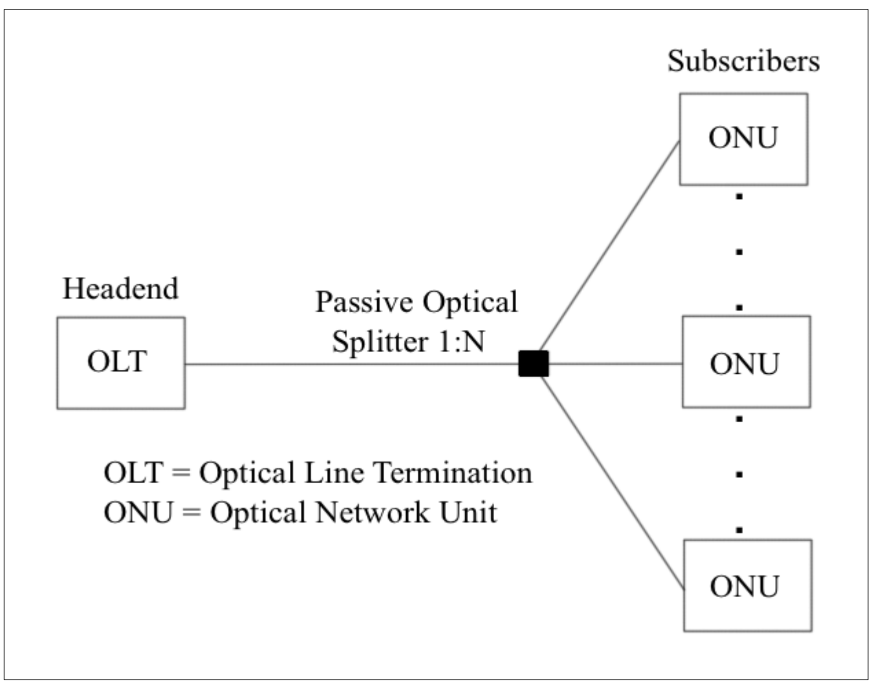



Figure 2.1: Architecture of PON

The amount of the power that will go to each subscriber is the total power entering the optical splitter divided by the number of subscribers in case the optical splitter's power is evenly divided [*10*]. According to the application and the design of the system, unequal and equal division of the optical power of the splitter can be used. The optical splitter can be designed in order to deliver several paths to different users ranging from 2 to 64. Nevertheless, the optical splitter could deliver 8, 16, or 32 paths in the PON model [*10*].

According to ITU-T and IEEE, the passive optical networks are networks that have an OLT with an active transmitter [*8*]. Also, an ONU can have either an active transmitter, or it can use the received power again in order to send data [*8*]. Other than OLT and ONU, all the components between the two should be passive, so they do not require an external power supply [*8*].

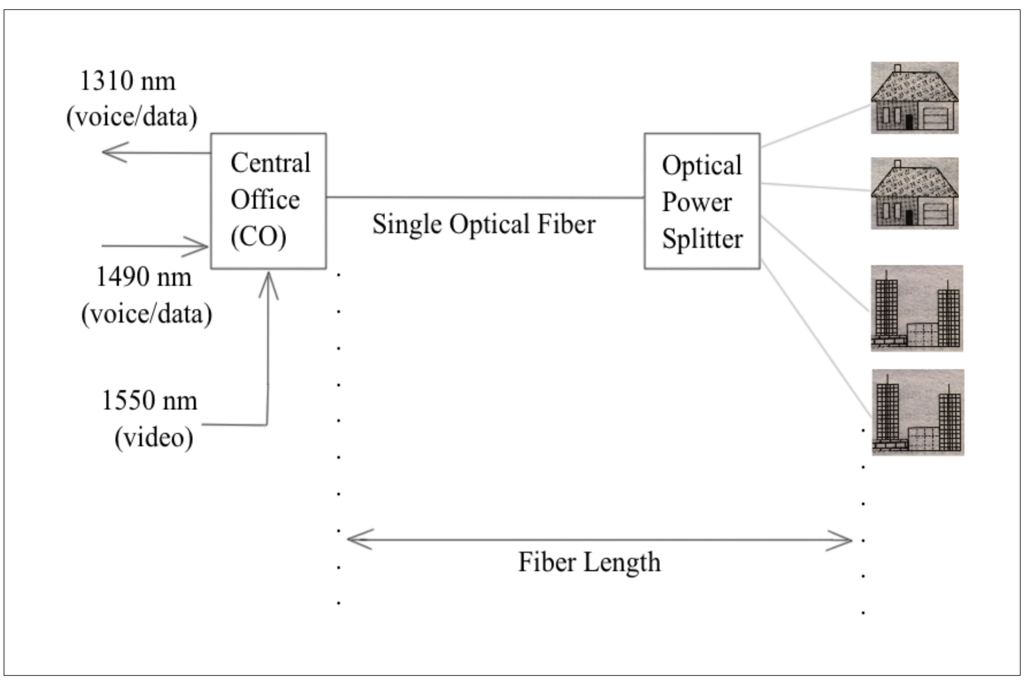



Figure 2.2: PON model

### 2.1.1 Low-Cost Components in PON Network

The maintenance and powering of active network components are two main factors of cost sources in the network. Therefore, PON is created in order to overcome that issue. The idea behind using PON is to utilize passive equipment that does not demand any kind of power source and maintenance. This passive equipment is in charge of distributing the information between the OLT and number of ONUs. Two kinds of technique can be utilized in order to distribute the information, which are the TDM-PON and WDM-PON techniques [*12*]. The passive optical splitter and combiner are responsible for splitting and combining the power in the TDM-PON architecture. In the downstream direction, the optical splitter divides the power coming from the OLT and cascades it to several ONUs in the system [*12*]. On the other hand, in the upstream direction, the optical combiner combines the power coming from the ONUs into a single optical fiber toward the OLT. The same process will happen in the WDM-PON architecture but using Arrayed wavelength gratings (AWG) instead of an optical power splitter and combiner.

Although components used for transportation in the PON architecture can operate without the need of electronic equipment, fibers such as OLT and ONU demand power transceivers at terminating ends [*12*]. Since the OLT in the service providers side requires just one transceiver to communicate with several ONUs in the subscribers side, the cost-efficiency can be maintained [*12*]. Also, because the OLT and ONU are found in places where the electric power is available, the power feeding does not frequently require further costs [*12*].

### 2.1.2 Time Division Multiplexed PON (TDM-PON)

Time division multiplexed passive optical network (TDM-PON), which is initially indicated as telephone on PON, is the most popular commercial PON structure. Bidirectional transmission in the PON structure depends on wavelength division duplex (WDD) [*13*]. Point-to multi-point (P2MP) optical splitter structure is shown in Figure 2.3. In the case of downstream direction, the OLT distributes the information by using an optical splitter to the entire ONUs in the access network. After that, all the distributed traffic is delivered to every ONUs. In order to differentiate different data for different ONUs, ONU address labels are inserted in the transmission [*13*]. At the ONU, all the data with incorrect address will be rejected, and all the data with correct address will be processed. TDM-PONs utilize encryption in order to secure the information [*13*].

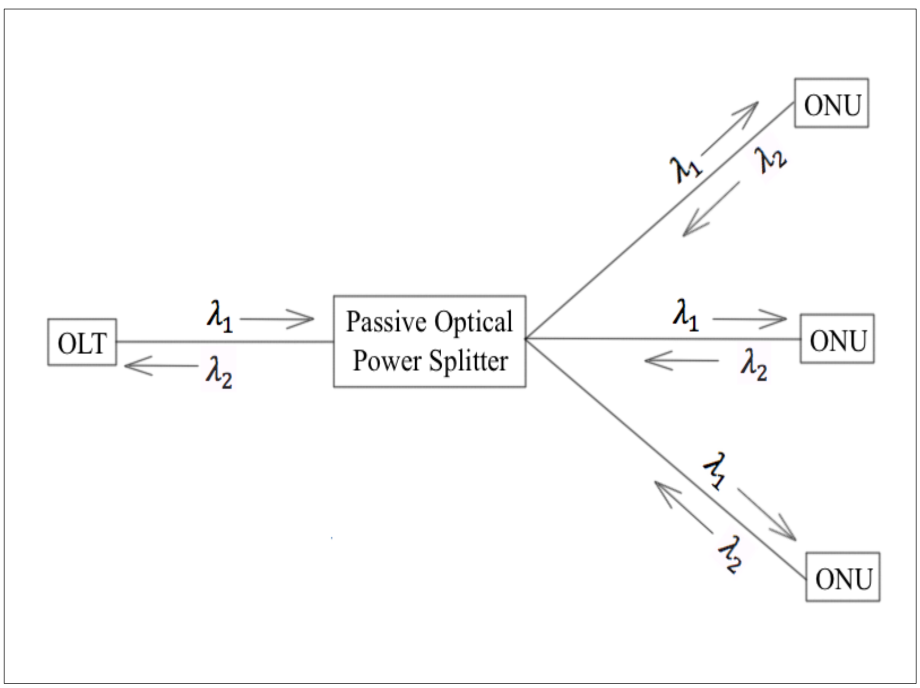



Figure 2.3: One-stage TDM-PON structure

The same optical power splitter combines the upstream ONU transmissions. The purpose of TDM is preventing the crashes between transmissions of various ONUs in the feeder network [*13*]. The TDM-based technique of the transmission area is indicated as time division multiplexed access (TDMA) [*13*]. In order for TDMA to be supported, a media access control (MAC) protocol is needed.

Based on the needed quality of service (QoS), flexible length transmission time space can be allocated for each ONU [*13*]. This technique is frequently known as dynamic bandwidth allocation (DBA) [*13*]. The price of the TDM-PON OLT can be shared between the users because of the P2MP structure.

### 2.1.3 Wavelength Division Multiplexed PON (TDM-PON)

The phrase wavelength division multiplexed passive optical network (WDM-PON) is utilized slightly roughly to define a PON that occupies wavelength division multiplexing (WDM) [*13*]. In the downstream direction, a popular characteristic is that the distinct wavelengths are used for each ONU. Either WDD or TDD can accomplish the traffic multiplexing in the upstream direction. Also, adiversity of different WDM-PON structures are achievable [*13*].

In the downstream direction, the utilization of a distinct wavelength offers wonderful traffic security because each ONU accepts only the information that is proposed for it. Diverse wavelengths can be allocated but diverse bit rates depend on the needed QoS [*13*]. The ONU equipment is able to operate at the received data rate. Because the WDM-PON OLT demands to have an array of transceivers to be able run on diverse wavelengths, it has a very expensive price [*13*]. Similar to the TDM-PON case, the price of the WDM-PON OLT can be distributed between the subscribers. Operation on diverse wavelengths has to be supported by WDM-PON ONU [*13*].

As shown in Figure 2.4, an array wave guide (AWG) router, which is a passive optical wavelength routing component, is frequently utilized as an RN [*13*]. In the downstream direction, as the function of the optical splitter in TDM-PON, the AWG router splits diverse wavelengths to diverse ONUs in the subscribers' side. AWG eliminates the splitting loss issue that would appear if a simple optical power splitter was utilized in its place. In the case of upstream direction, the AWG router basically passes over the entire transmitted wavelength within the transmission band [*13*].

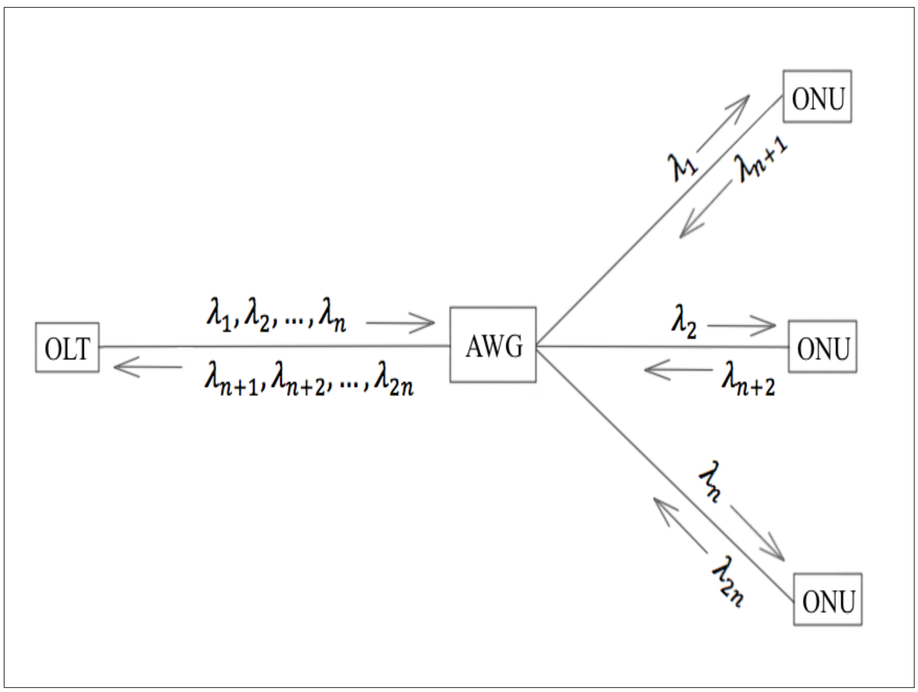



Figure 2.4: DWM-PON structure

### 2.1.4 TDM-PON versus WDM-PON

The two sections above discussed the TDM-PON and WDM-PON. In this section, the advantages and disadvantages of these two technologies will be presented. The bandwidth needed is continually increasing with the new services provided, and there are increases in the number of users demanding improved access network performance as well.

Two issues limit the performance of the TDM-PON technology. The first issue is that the ONUs have to operate at the total bit rate of the entire PON, and this makes the hardware design harder with larger transmission rates [*13*]. The second issue is that the splitting ratio limits certain factors. The splitting ratio limits the maximum number of ONUs desired in the PON system [*13*]. Because the channel is separated between the ONUs by the optical splitter, it also limits the bandwidth per ONU. Finally, the optical splitter limits the maximum reach of a PON system, which will result in decreasing scalability [*13*].

However, WDM-PON can be used to overcome all the disadvantages of the TDM-PON technology. Each ONU in the PON system using WDM technology runs on a separate bit rate, and this will result in relaxing the hardware needs [*13*]. In order to increase the reach and the scalability in the WDM-PON structure, AWG router is used. Finally, in order to deliver a high bandwidth per ONU, each ONU can assign its own wavelength [*13*].

Besides these advantages of the WDM-PON technology, it has one main disadvantage. The main drawback is that it is more expensive than the TDM-PON due to all the pricey equipment WDM-PON has [*13*].

**2.2 Fiber-To-The-X (FTTX)**

Three structures that are used as a [*9*]demonstration in standards of the “ITU Telecommunication Standardization Sector” (ITU-T) and “Institute of Electrical and Electronics Engineers" (IEEE) are shown in Figure 2.5 [*8*]. Many components are shown in Figure 2.5. The network is named as "Service Node Interface" (SNI) in the service providers side and "User Network Interface" (UNI) in the users side [*8*].

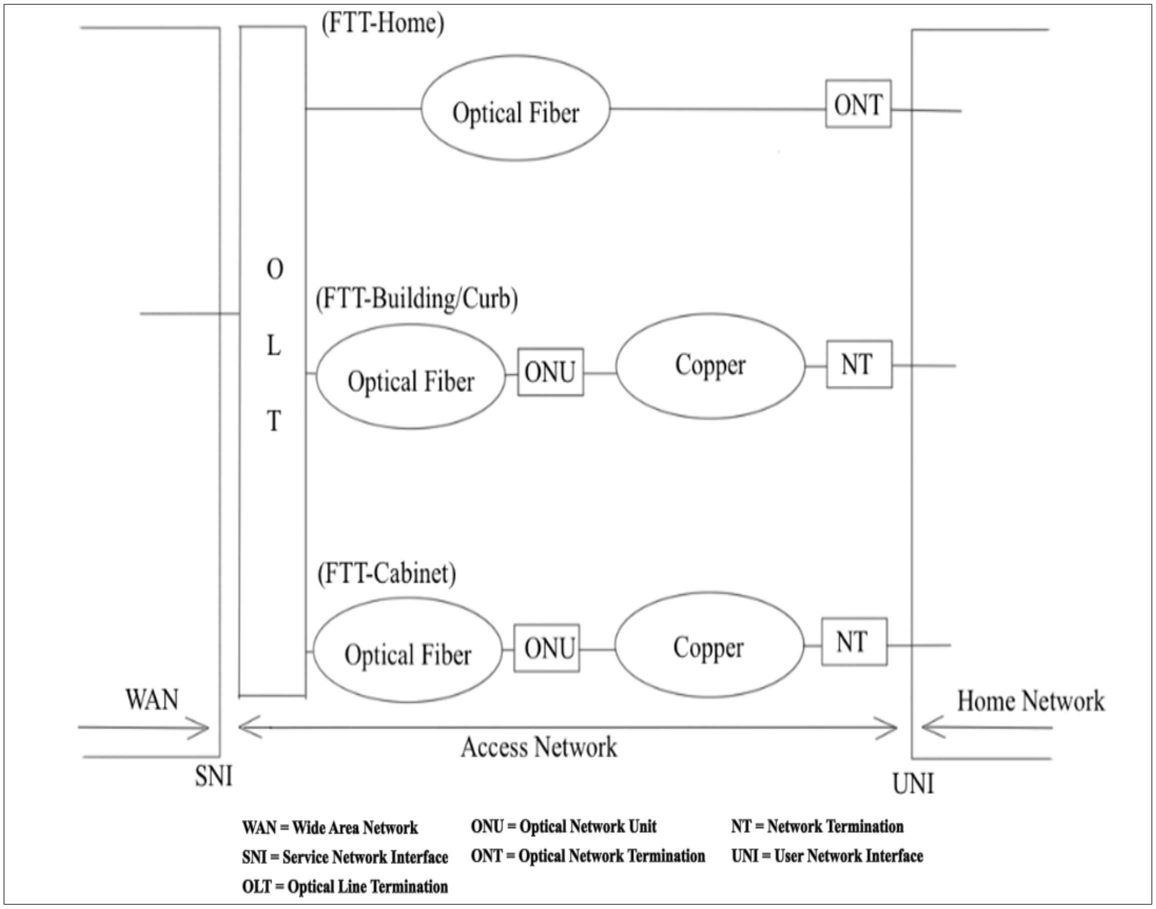



Figure 2.5: Network of optical network

The SNI to the network is made up of "Optical Line Termination" (OLT). OLT is the optical interface to the network. "Optical Distribution Network" (ODN) is the optical fiber which links between the SNI and UNI [*8*]. "Optical Network Termination" (ONT) or "Network Termination" (NT) is the termination point at the UNI. An "Optical Network Unit" (ONU) has to be settled if a NT is used at the UNI. This ONU has two main functions which are terminating the optical fiber and converting the signal from optical to electrical [*8*]. The two components, NT and ONU, are combined into a single component which is ONT. As shown in the Figure 2.5, each structure has its own name such as FTT-Home and FTT-Cabinet [*8*].

In structures like FTTCab, FTTC, and FTTB, the optical fiber ends up in a cabinet or patch-box where the optical signal is converted to electrical signal by the ONU. Copper cables attach the distance between the ONU and NT [*8*]. Some examples of these structures are TV distribution in residential district, abundant office buildings, and telephone distribution [*8*]. In these structures, optical fibers deliver the large capacity bandwidth to a district where single copper cables will provide the signal to the subscriber [*8*].

## 2.3 Elements of a Bidirectional Optical Link

### 2.3.1 Optical Source

The function of the optical source is to generate light energy in order to transmit traffic after modulating the light signal with the electric signal. Semiconductor components are utilized for transmitting the traffic although there are various techniques to generate light [*14*]. Examples for these various techniques involve light emitting diode (LED) and diode lasers.

There are many advantages of utilizing these kinds of components. One advantage is that they are simple to activate and assimilate with electronic circuits [*14*]. They all behave as a diode [*14*]. This means they need a forward voltage that will result in a current flow in order to operate them. When more optical power is needed, all that will need to be done is increasing the current. However, in order to turn them off, switching the current off is required. Therefore, in various applications, the modulation of light is accomplished by controlling the current. Another advantage of using semiconductor components as optical sources is that they are very efficient [*14*]. Semiconductor components also have an essential advantage regarding the optical wavelengths they generate [*14*]. In addition to these mentioned advantages, semiconductors are very reliable, very small, and inexpensive [*14*]. These advantages allow for semiconductors to be used in communication very often.

Although the LEDs are cheaper than the lasers, they are used in low data rates and short distance applications [*14*]. The major disadvantage of the LEDs is that they have a wide spectrum width of their light output [*14*]. Therefore, this main disadvantage causes high dispersion as the light propagates over the fiber. This is the reason why LEDs cannot be used in long distance applications or high modulation rates in the optical communication area. However, lasers have very narrower spectral width. Thus, they are favored in long distances application [*14*].

### 2.3.2 Erbium Doped Fiber Amplifier (EDFA)

In the late 1980s and early 1990s, the EDFA was densely researched [*9*]. For optical communication systems, the EDFA is the most essential design. It is difficult to have a transmission across the ocean employing WDM or metro access network without the help of this creative invention [*9*].

A silica fiber doped with erbium, called erbium doped fiber amplifier (EDFA), is a well-known component for long haul telecommunication purposes [*10*]. The operating areas of these types of components are based on the doping elements and the host material [*10*]. Occasionally, ytterbium (Yb), which is a chemical element, is utilized in the EDFA's design in order to boost the efficiency of the pumping and the amplifier gain. 1530 to 1565 nm wavelength, which is the C-band or conventional band, is the region where the operation of the EDFA is limited [*10*]. Several techniques have been utilized in order to increase the operation region to the S- and L-band [*10*]. The ranges of some of the bands are described in Table 2.1.

| Name | Abbreviation | Spectral Range (nm) |
|---|---|---|
| Original Band | O-band | 1260-1360 |
| Extended Band | E-band | 1360-1460 |
| Short Band | S-band | 1460-1530 |
| Conventional Band | C-band | 1530-1565 |
| Long Band | L-band | 1565-1625 |
| Ultra-Long Band | U-band | 1625-1675 |

Table 2.1: Names and spectral ranges of regions used in optical fiber communication [*10*]

The EDFA has an abundance of essential advantages in the optical communication area. First, the loss is minimal when the gain is at 1555nm wavelength. [*9*] Second, it provides large gains with large gain efficiency [*9*]. Third, the noise of EDFA is only 3dB at high gain [*9*]. Finally, it has low polarization dependence and channel-to-channel crosstalk [*9*]. The EDFA has very weak polarization dependence. However, it becomes serious when a lot of amplifiers are distributed [*9*].

The EDFA is presented and used in almost all communication structures. Other applications besides the use of EDFAs as an amplifier in the communication system includes its use in fiber lasers. [*9*]. While there was an attraction towards low fiber laser in the mid-1990s, the attraction has been directed to high power fiber lasers in the past decade [*9*].

### 2.3.3 Power Splitter Architectures in a TDM-PON

#### *2.3.3.1 Splitting Structures*

Two reasons for power splitting are distributing the price and bandwidth of OLT between ONUs and decreasing the distance of the fiber in the system [*4*]. Figure 2.6 (a) shows one type of splitter architecture which is a straightforward one-stage splitting approach [*4*]. However, the splitters can be distributed in the system as shown in Figure 2.6 (b). In Figure 2.6 (c), the third type of splitting architecture is shown where the optical fiber configures an optical feeder and ONUs are attached to it at different locations along its path.

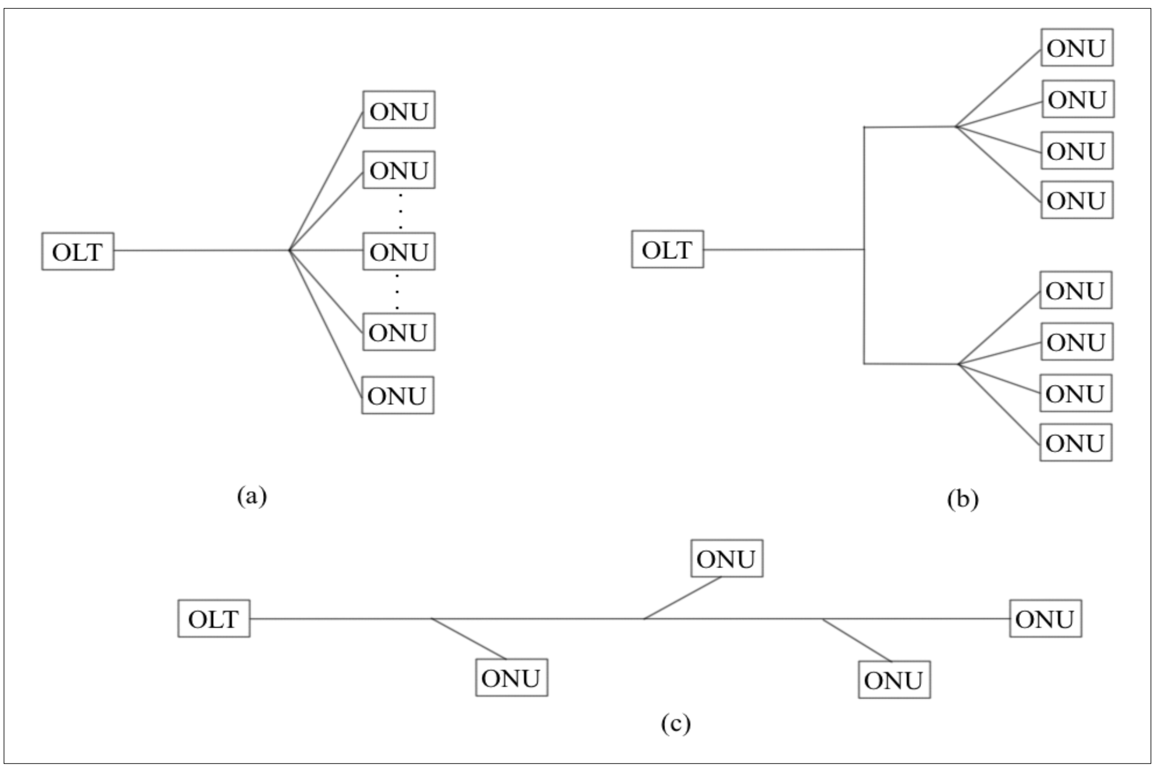



Figure 2.6: Power splitter architectures in a TDM-PON: (a) one-stage splicing, (b) several stage splicing, and (c) Optical feeder bus

Using specific architecture depends on the subscribers' demography and the price to handle many splitters. The opinion of management is that it is often easier to have an individual splitter for cascading than have many of them [*4*]. This is because of two reasons: simplicity in splicing and reducing the connectors and splicing losses [*4*]. For example, a one stage splicing approach offers simple network maintenance, reduced splicing, and connector losses. However, it increases fiber distance [*13*].

One main disadvantage of the third architecture which is shown in Figure 2.5 (c) is that the farthest ONU will suffer the most transmission and splitting loss [*4*]. In order to overcome this disadvantage and increase the whole power margin, uneven splitting rations might be used. Nevertheless, such a strategy needs non-uniform splitters, and it is hard to handle [*4*].

#### *2.3.3.2 Splitting Ratio*

1:16 or 1:32 is a splitting ratio, which the majority of the commercial PON systems have [*4*]. The price of the PON OLT is well shared between ONUs when a higher splitting ratio is used. Nevertheless, the system power cost and transmission loss is affected by the splitting ratio straightforwardly. For 1:N, the ideal splitting loss is $10 \times \log(\mathrm{N})$ dB. Large power transmitters, low loss optical apparatuses, and high sensitivity receivers are needed in order to help higher splitting ratio and to handle the losses [*4*] [*13*]. A large splitting ratio permits a decrease in the distance of optical fiber in the system and distributes the price of OLT between more ONUs [*13*]. On the other hand, it has an instant effect on the system power budget and transmission loss [*13*].

As known, OLT bandwidth is shared between ONUs. Therefore, a larger splitting ratio will result in less bandwidth per each subscriber [*4*]. This restricts the highest number of users in the PON structure [*13*]. A minimum energy per bit is needed to defeat the system noise in order to accomplish a specific bit error rate (BER) performance. Thus, at the OLT, increasing the bit rate will also increase the power, which includes the amount of bit rate and bit energy needed for transmission [*4*].

### 2.3.4 Optical Circulator

In the late 1970s and early 1980s, different applications of optical circulators have been broadcasted and have continued since then, involving various “ideal” four-port circulators [*9*]. A passive multiport and a non-reciprocal component are called an optical circulator. Its function is to guide light from port to port, which results in separate signals that might travel along the optical fiber in the opposite direction. The basic optical circulator consists of three or four ports. Basic features of these early components have an insertion loss of 2dB, isolation of 25 to 35 dB, and 1.3μm operation wavelength [*9*]. A very complex design is required in order to have high performance of an “ideal” circulator. Therefore, the optical circulators are offered with less performance. However, the high performance is not needed. In situations such as having a four ports optical circulator, the related routing features can be that the only input port is the port numbered 1; ports numbered 2 and 3 can be used as input and output ports while port numbered 4 can be used as an output port only. In the case of having a three ports optical circulator, they may have port numbered 1 as the only input port, port numbered 3 can be used as output port only, and port numbered 2 can be used as an input and output port [*9*].

Ideally speaking, a four ports optical circulator would have four inputs and four outputs. There are three areas that are add/drop multiplexers, optical amplifiers, and dispersion compensation modules in which the optical circulator can be used

[*10*]. The components used in designing the optical circulator are half wave plates, Faraday routers, and walk off polarizers [*10*]. One essential feature of the optical circulator is that it has high isolation over a wide wavelength range, and thus it can be used as an isolator as well. However, the optical circulators have a sophisticated design. Some of the other features that optical circulators have are minimum insertion loss, low polarization dependent loss (PDL), and low polarization-mode dispersion (PMD) [*10*].

#### 2.3.5 Optical Detectors

The optical detectors are most likely to be semiconductor components that have the design of either PIN diode or avalanche photo diode (APD) detectors. Repeatedly, these two kinds of diodes are the usual diodes that can be forward or reverse biased. However, in order to operate as detectors, they have to operate in the reverse biased [*14*].

PIN diodes have many advantages. One of the advantages is that it can operate with a very low reverse bias. Therefore, a circuit with a voltage such as 3.3V can run the PIN diode [*14*]. The PIN will generate a current, which is proportional to the power of the received light. That means that the detector can also be dealt with as a light-controlled current source [*14*].

In the case of APD detectors, a very high reverse bias voltage is demanded in order to run. The lowest voltage that APD detectors demand ranges from 30V to 40V of reverse bias [*14*]. In addition, for APDs, the best-needed reverse bias voltage depends on temperature [*14*]. As the temperature increases, the reverse bias done to the APD detector has to be increased in order to keep the gain of the APD constant. Also, APDs are more costly than the PIN detectors [*14*].

## 2.4 TDM PON Infrastructure

In the TDM-PON structure as shown in Figure 2.7, an OLT is connected to the ONUs via an optical splitter. BPON, EPON, and GPON use the same structure shown in Figure 2.7. An OLT is linked to 32 ONUs through an optical splitter, having a 1:32 splitting ratio [*4*]. 10 to 20 km is the maximum distance that can be covered using TDM-PON. 1.49 µm is transmitted in the downstream direction from the OLT to the ONUs and 1.3 µm is transmitted in the upstream direction from the ONUs to the OLT [*4*].

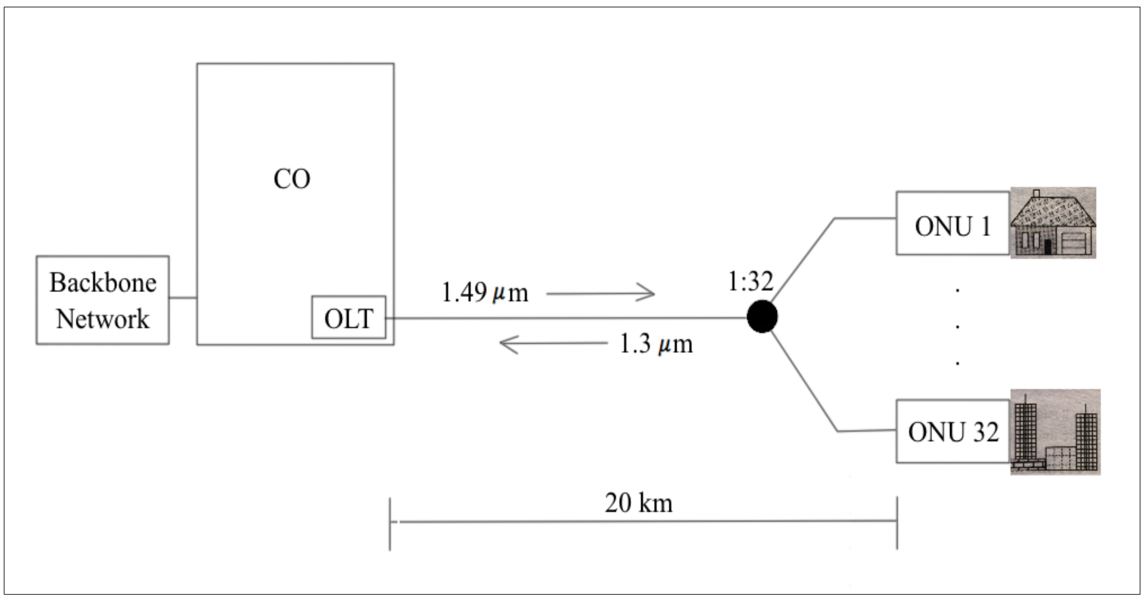



Figure 2.7: TDM-PON Infrastructure

ONUs offer one port for voice connection or more and customer data connections. The backbone switch is interconnected with one or more OLTs in the CO. The PON section can be named as the connection between the OLT and the ONUs [*4*]. Based on the type of PON implemented, the signal transmitted to the PON section can be encoded and multiplexed with various formats and arrangements [*4*].

Signals from and to various ONUs are frame inserted in the PON section. In the frame heading, each frame is recognized with a special ONU ID [*4*]. In the downstream direction, the connection is a one-to-multi-subscriber because of a 1:N optical splitter [*4*]. Nevertheless, in the upstream direction, the connection is multi-subscriber-to-one. Therefore, frames that have been sent from the ONUs will arrive to the OLT. However, the data cannot be sent directly among two ONUs in the optical layer [*4*]. Therefore, the connection between ONUs must be transmitted to the CO with the help of the OLT [*4*].

### 2.4.1 OLT Structure

The optical line termination (OLT) is located in the central office. The main purpose of the OLT is to organize the bidirectional traffic of information such as data, voice, and video within the network. An OLT has to handle transmitting the information through the specific distance between the central office to the ONUs in the subscribers side. In the downstream direction, an OLT in the service providers' side has to deliver the information to the optical splitter, and the optical splitter will then distribute the information to the subscribers. On the other hand, in the upstream direction, an OLT has to admit and spread out different types of data and voice traffic from the network subscribers. A regular OLT is built to be in charge of more than one PON.

The downstream and the upstream transmission direction traffic components run at 155Mb/s, 622Mb/s, 1.25Mb/s, or 2.5Mb/s according to the PON standard being used. Depending on the application, the data rate might be the same for both directions. On the other hand, the downstream might have a higher data rate than the upstream traffic. Therefore, the data rate is not required to be equal for both downstream and upstream traffic.

### 2.4.2 ONU Structure

Close to the subscribers' properties, the optical network units (ONUs) are located in outdoor equipment housing. This equipment would contain housings placed at a curb or in a central place inside an office park. Therefore, this ONU equipment has to accommodate to environmental variations and temperature changes. The housings containing the ONUs have to have resistance to water and have the ability to resist high wind. Furthermore, there should be a local power source to operate the components that are needed to be operated and battery as a backup in case of emergency situations. A coaxial cable, twisted-pair copper wire, a wireless connection, or an optical fiber can be used in order to connect the ONUs to the subscribers' properties.

## Chapter Three: PON standards Overview

In addition to the Broadband PON (BPON), there are two other standards of PON, which are Ethernet PON (EPON) and Gigabit PON (GPON). EPON is one type of PON standards that transmit data traffic in Ethernet frames. One main disadvantage of using EPON is its high cost [*15*]. One of the essential advantages of using GPON is that the links to all vital services are supported. The first time division multiplexing (TDM-PON) system was improved by FSAN and it was called Broadband Passive Optical Network (BPON) [*16*]. BPON depends on Asynchronous Transfer Mode (ATM). It is frequently referred to as Asynchronous Transfer Mode Passive Optical Network (APON).

| **Technology** | **Standard** | **Distance (km)** | **Maximum Splitting Ratio** | **Downstream (Mb/s)** | **Upstream (Mb/s)** |
|---|---|---|---|---|---|
| **BPON** | G.983 | 20 | 1:32 | 155,622,1244 | 155,622 |
| **GPON** | G.984 | 20 | 1:64 | 1244,2488 | 155 - 2488 |
| **EPON** | 802.3 | 10 | 1:32 | 1244 | 1244 |

Table 3.1: BPON, GPON, and EPON standards details [*17*]

In 1998, ITU-TG.983 series recommendations released the first BPON standards [ITU09] [*1*]. BPON has flexible architecture and can accommodate with various situations. The data rates and user data encapsulation technique are two main differences between BPON and GPON. Two main parts of BPON's architecture are OLT and ONU. Three PON standards details are shown in Table 3.1.

## 3.1 Broadband PON

The broadband passive optical network (BPON) standard was the first PON standards introduced [*18*]. BPON was agreed by ITU in 1999 [*18*]. BPON standards rely on the G.983 series of ITU-T recommendations [*11*]. The G.983 series of ITU-T recommendations affirm that the ATM is the transference and signaling protocol [*11*]. Occasionally, access networks depending on the BPON standard are called APONs [*18*]. Several network suppliers and components sellers that collaborated together in the FSAN group endorsed the BPON standard [*18*]. The fact that the ATM protocol should be utilized to carry subscribers data was suggested by the FSAN group [*18*].

The telecommunication services carriers are utilizing BPON technique to expand the fiber-to-the-premises (FTTP) networks because these carriers have a wide embedded switching structure [*11*]. Two advantages of ATM networks besides being a verified technique are its abilities to have scalable and flexible traffic management and its robust QoS features [*11*].

### 3.1.1 BPON Structure

#### *3.1.1.1 Traffic Flow Constructions*

1490nm wavelength is utilized in the downstream traffic direction in order to transmit data and voice services. At the OLT, this collection will be compressed in ATM cells by the switching components [*11*]. ATM is a combination of information and a control header [*11*]. Information occupies 48 bytes and another 5 bytes are occupied for the control header. For the downstream traffic, 1.2Gb/s is the maximum bandwidth that can be offered by the BPON according to the G.983 standard [*11*]. The same fiber that is used to transmit the downstream traffic is also used to transmit the upstream traffic. 1310nm is the wavelength used to transmit data and voice services by the ONT for the upstream. 622Mb/s data rate can be used for the upstream traffic according to the BPON standard [*11*].

In order to send video service in the downstream direction from the OLT, 1550nm wavelength is required [*11*]. Video distribution is one main application for this one-way downstream traffic [*11*]. Video distribution permits the user to utilize a set top box in order to choose any of a large set of TV channels. This video service transmission is transmitted in another packet from the data and voice collection [*11*]. It is separately transmitted from the ATM-encapsulated data and voice traffic. This video service can be transmitted in both analog and digital formats at the same time and in different frequency bands. Through the same fiber and by using 1550nm wavelength, standard TV and high-definition TV (HDTV) can be transmitted at the same time [*11*]. While downstream 1490nm data and voice traffic is sent utilizing TDM of the ATM cells, upstream 1310nm data and voice traffic is sent by utilizing TDMA protocol [*11*].

#### *3.1.1.2 OLT Abilities*

In a network, an indivisible OLT is capable of achieving a number of distinct PONs at the same time. Thus, one single OLT is able to achieve 22 BPON lines that can deliver data, voice, and video to 702 clients if the optical splitter is a 1:32 ratio, as can be shown in Figure 3.1 [*11*]. In situations such as failing line or circuit card, an OLT involves the height levels of carrier-class redundancy stated for protection when switching in SONET/SDH components [*11*] [*11*]. The size of a standard OLT shelf permits four units to fit into one 2m rack, which permits data, voice, and video services to be distributed to 2816 clients per component rack [*11*].

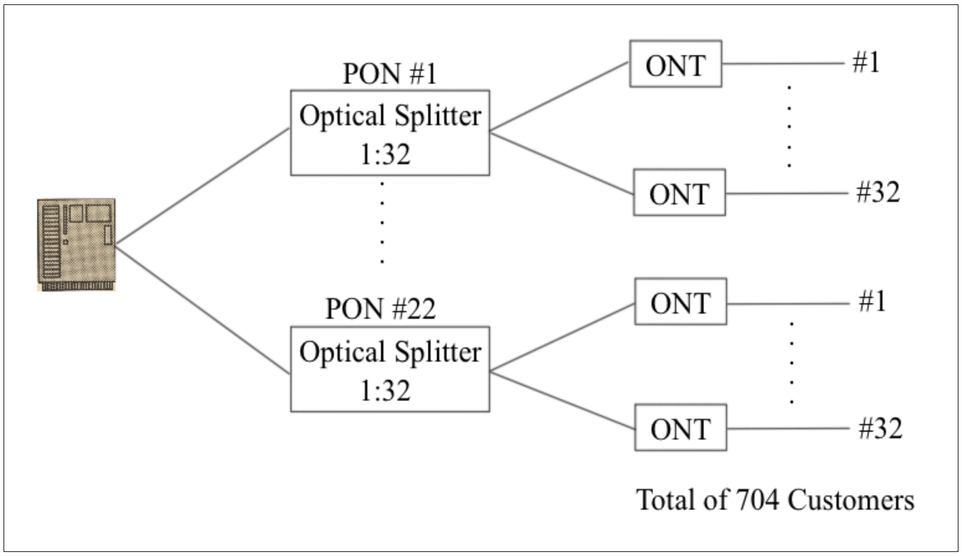



Figure 3.1: OLT abilities

### 3.1.2 BPON Operational Features

In BPON, there are three essential factors in order to achieve high quality of service performance. These are suitable synchronization of upstream traffic through the shared PON media, organization of buffer content at the ONTs, and effective bandwidth use [*11*].

#### *3.1.2.1 Flows of Data and Voice Traffic*

The OLT that is located in the central office is the one responsible for the interface between the exchange carrier network and the users on the BPON network [*11*]. The information is transmitted in the form of ATM cells to the entire ONTs by the OLT on the BPON network utilizing a TDM structure when the information in the form of data or voice reaches the OLT from the carrier network [*11*]. 155.52, 622.08, and 1244.16 Mb/s are three options of the BPON network in the downstream direction [*11*].

Each single ONT has to be synchronized with all the ONTs in the system because they utilize TDMA in order to transmit information to the OLT [*11*]. A ranging process is utilized by the OLT in order to accomplish this synchronization. A ranging process determines the distance between the OLT and the ONTs [*11*].

#### *3.1.2.2 Video Traffic*

A head-end transmitter is one component that transmitting videos relies on. The function of the head-end transmitter is receiving content from various analog and digital sources., the transmission system distributes video traffic to subscribers using the same standard user multiplexed modulation structure that the CATV utilizes [*11*].

The overlay is transparent to the other data and voice traffic is transmitted through the same fiber at 1490nm because it utilizes a separate 1550nm wavelength [*11*]. Therefore, any coding technique can be utilized for the video [*11*]. Coding techniques involve 64 or 256-point quadrature amplitude modulation (QAM64/256), quadrature phase shift keying (QPSK), and others [*11*].

An optical amplifier is located directly after the video transmitter is utilized in order to increase the optical signal level before it is transmitted out through the BPON feeder cable [*11*] [*11*]. This amplification that the optical fiber will do to the signal is essential to have enough optical signal-to-noise ratio (SNR) for the video signal at the customers' side [*11*].

## 3.2 Gigabit PON

Two main reasons for trying new PON models are that a large bandwidth has to be achieved in order to make a progress and the complexity of the ATM design, so FSAN took a second look at its ATM [*7*]. The scope of the ITU-T recommendation series

G.984 is to offer a flexible fiber access network that is able to support the required bandwidth to residential user homes and businesses [*12*]. Therefore, in 2003, a new PON model, which is called GPON was invented by ITU [*7*]. The aim under designing the GPON model is to improve the BPON by reexamining the supporting services, optical fiber structure, and security policy [*12*]. In addition, GPON is designed in order to maintain as many features as possible from the BPON recommendation to overcome some of the existing drawbacks.

Although GPON is no longer dependent on ATM as an original protocol, its range of capabilities was deeply dependent on its ancestor [*7*]. In its place, an abundant easier generic framing procedure (GFP) is utilized to deliver support for both data and voice services. The most useful factor of the GPON over other PON models is that interfaces to the entire major services are offered. Use of GFP guaranteed that packets fitting to various protocols could be sent in their native formats [*7*]. In addition, a range of capabilities was offered that permitted smooth agreement with other GPONs and BPONs. The security of the sent data is a major essential factor in the modern networks. For this reason, some components are integrated in the GPON structure such as a complicated mechanism that depends on the advanced encryption standard (AES) and complex exchange of unique keys [*7*].

Transmission with higher rates is possible in GPON model comparing with BPON. A GPON model is capable of sending data rates up to 2.48Gb/s in both the downstream and upstream traffic directions. Developing a multipurpose PON architecture with a frame format that has the ability to send multiple length packets with high performance at Gb/s rates was the major goal [*11*].

### 3.2.1 GPON Structure

As can be seen in Figure 3.2, a layout of GPON architecture and features are shown. It has the same range of capabilities as in BPON and EPON schemes [*11*]. Nevertheless, GPON architecture has an advantage over BPON and EPON architectures. This advantage can be considered as the GPON operational scheme has a design that is more customer-driven [*11*] [*11*].

In March 2003, ITU-T approved the G.984 [*11*]. This recommendation provides general features such as the GPON structure, the wanted bit rates, optical power splitting ratios, kinds of services to accomplish, information security, and signal transfer delays [*11*]. In order for the GPON model to be compatible with the BPON model, some requirements of the BPON G.983 recommendation is maintained by G.984 [*11*].

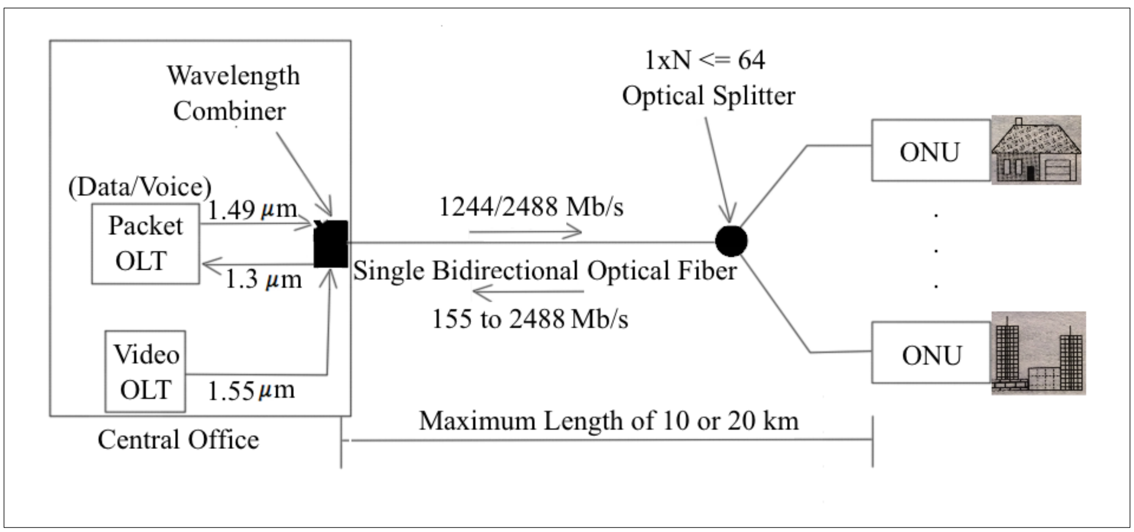



Figure 3.2: Architecture and features of GPON

### 3.2.2 GPON Information Security

Every massage sent might be seen by all the subscribers linked to the GPON system because the downstream traffic is transmitted from the OLT and distributed to all the ONTs [*11*]. The same situation happens to other PON architectures. Therefore, the use of an information security instrument is described by the GPON standard in order to certify that the subscribers are permitted to access just the data intended for them. The advanced encryption standard (AES) is one example of other examples of a point-to-point encryption instrument [*11*] [*11*]. AES is utilized in order to protect the information loaded of data fields in the GPON system. In order to protect data, it is transmitted into an unintelligible format at the sending end from utilization, modification, destruction, or unauthorized disclosure. This is a technique called encryption [*11*]. A key has the ability to be changed regularly, for example one time per hour, without disturbing any of the information flow.

#### 3.2.3 ONT Management and Control

ONT management and control, which is abbreviated by OMCI, is defined by the ITU-T recommendation G.984.4 for the GPON model [*11*]. The ONT management and control (OMCI) for both the GPON and BPON models are identical [*11*]. The area that has the difference between the GPON and BPON is the management of the GPON encapsulation method (GEM) [*11*]. Nevertheless, GEM has the ability to be managed utilizing the same entities and procedures that are utilized for the same transport service because it is a connection-oriented protocol [*11*].

### 3.3 Ethernet PON

Compared to ATM models, EPON seems to have achieved the position of a worldwide network protocol [*13*]. In September 2004, IEEE approved the Ethernet in PON technology [*13*] [*7*]. This Ethernet-based PON is named EPON. However, it is also known as Gigabit EPON (GEPON). In the EPON model, 1.25Gb/s data rate can be transmitted in both the downstream and upstream traffic directions [*13*]. 20% of the line rate is lost because of 8B/10B line coding, which is mapping 8 symbols to 10 symbols [*13*]. Therefore, 1Gb/s is referred to be transmitted in both the downstream and upstream traffic directions [*13*].

The majority of the traffic in the network is data, so the FSAN group decided that the complex functionality of the BPON and the GPON protocols were no longer required [*7*]. In its place, as the Ethernet protocol had become well known and popular, the EMFA decided to support its functionality in PON [*7*]. Accomplishing a full compatibility with other Ethernet based networks was the major aim [*7*].

### 3.3.1 EPON Structure

Figure 3.3 presents the EPON architecture and its features. The maximum branches that go out from the optical splitter to the ONTs are 32 [*11*]. As stated by the IEEE, the maximum transmission distance between the OLT and the ONT is 10 or 20 km [*11*]. The transmission distance is according to the branches that the optical splitter provides [*11*].

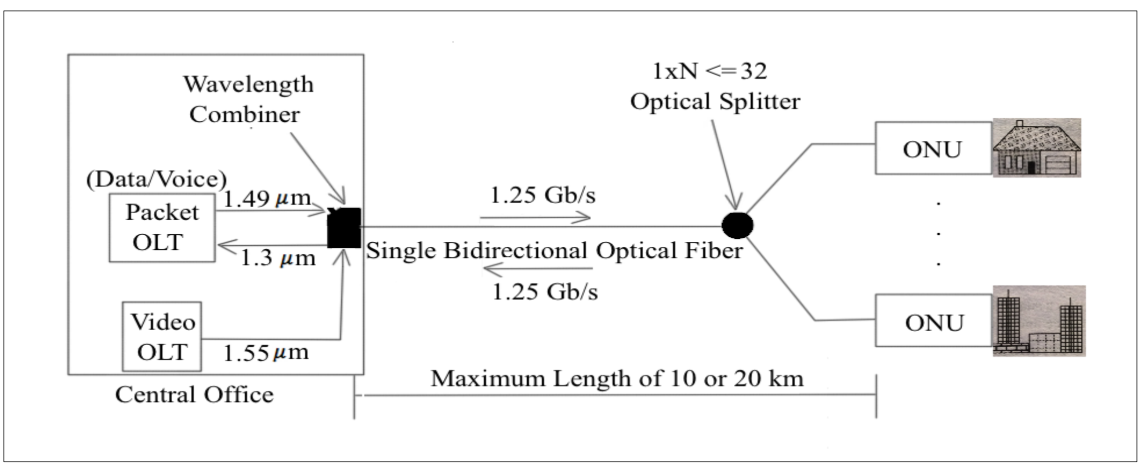



Figure 3.3: Architecture and features of EPON

MAC and physical layer (PHY) chip sets are utilized to the EPON applications [*11*]. EPON utilizes 1490nm wavelength in the downstream traffic from the OLT to the ONT for both data and voice, and 1310nm wavelength for the upstream traffic from the ONT to the OLT. Therefore, 1550nm wavelength is available for other services such as transmitting video from the OLT to the subscribers.

##### *3.3.1.1 OLT and ONT/ONU Purposes*

OLT's function in EPON architecture is used as a network controller, which is similar to other PON architecture [*11*]. There is no interaction between the ONTs on the EPON architecture since the entire communication happens between the OLT and the ONTs [*11*]. Some of the OLT's functions will be mentioned in this section. One function of the OLT is continuously determining if any ONTs have linked or gone from the network. This process is called the discovery process [*11*]. OLT has the ability of controlling the registration of recently combined ONTs [*11*]. The OLT can also allocate different amount of upstream traffic bandwidth to each ONT [*11*]. In addition, OLT achieves a ranging process in order to compute the transmission time delay between the OLT and each ONT [*11*].

#### 3.3.2 10 Gigabit Ethernet PON (10GEPON)

The IEEE developed a next-generation EPON standard, called a 10 gigabit Ethernet passive optical network (10GEPON) [*13*]. This invention was developed in order to address the increasing bandwidth needed. In September 2009, the 10GEPON standard was published [*13*]. It has the capability of transmitting 10.3125Gb/s in the downstream traffic and the same amount of Gb/s in the upstream traffic [*13*].

### 3.3.3 Point-to-Point Ethernet

#### *3.3.3.1 Point-to-Point Ethernet Through Fiber*

P2P Ethernet fiber utilizes single alternative fibers for P2P Ethernet access networks. In this situation, there are devoted fibers linking the central office with each user. Therefore, it is required to have many optical fibers running from the central office to each subscriber, and every optical fiber has its own optical transceiver. For instance, assume that the network has to transmit information to 16 users. If the optical link, which is the optical fiber, between the central office and the users is bidirectional, this case needs 16 fibers. In the situation that the optical link is unidirectional, 32 optical fibers are demanded and 32 optical transceivers are required because each user needs transmitters and receivers at each end. Therefore, a total of 32 optical transceivers are needed [*11*]. As a result of the features discussed, this kind of technology is suitable only if each user demands close to the full capacity offered by a high-capacity Ethernet line.

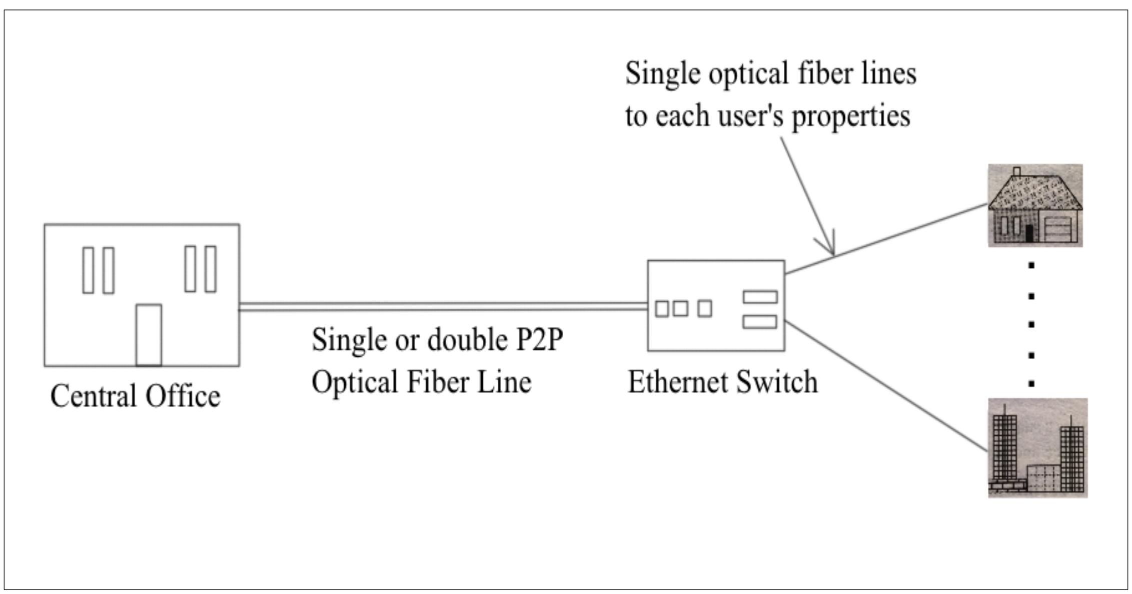



Figure 3.4: P2P Ethernet over fiber by using Ethernet switch

Another technique is to utilize one bidirectional or two unidirectional optical fibers from the central office to an Ethernet switch placed close to the users. This technique is shown in Figure 3.4. Single optical fiber lines can be linked from the Ethernet switch to each user's properties. This type of technique has the advantage of significantly reducing the number of optical fibers interfacing to the central office. However, it has a disadvantage that the Ethernet switch demands external electrical power located in the outside cable plant. Another disadvantage is in addition to having 32 transceivers between the Ethernet switch and the users, there has to be two or more transceivers between the central office and Ethernet switch.

# Chapter Four: Simulation Results

## 4.1 Introduction

Optisystem is a powerful tool of designing and testing almost every component and element included in the design. By utilizing this kind of innovative software in real life, designers will have the opportunity to reduce both the time and cost of the system by simulating the system before starting to build it. It can be used to analyze the performance of the optical communication system. The 12th version of Optisystem has been utilized in order to simulate the desired BPON system, which is shown in the Figure 4.1.

Measuring Devices such as spectrum analyzers or power meters measure parameters related to single devices or tests. Nevertheless, it is essential to study and measure the performance of a whole system having several components. A whole system starts, for example, with an optical transmitter such as a laser, optical fiber, and ends with an optical receiver. For that reason, the ultimate measurement of the performance for optical communication system is bit error rate (BER). BER can be defined as the ratio of the correct received bits to the whole number of bits transmitted. Besides measuring an entire link, BER also has the ability to measure many digital circuits and systems such as clock and data recovery circuits. PRBS for various lengths is one of the most popular patterns for testing BER.

## 4.2 Simulation Set Up

Figure 4.1 is the simulation set up which is used to analyze the performance of the signal in both downstream and upstream traffic. As can obviously be seen from the Figure 4.1, components such as the CW laser, pseudo random bit sequence generator (PRBSG), non-return-to-zero (NRZ), return-to-zero (RZ), optical circulator, single optical fiber, EDFA, and BER analyzer have been utilized. A list of almost the entire parametric values adjusted in the optical simulation depending on standard network values is shown in Table 4.1. Downstream traffic is transmitted through the optical fiber at the wavelength of 1550nm and the upstream traffic is transmitted at the wavelength of 1300nm. One of the lowest possible attenuation windows occurred when these two wavelengths had been used.

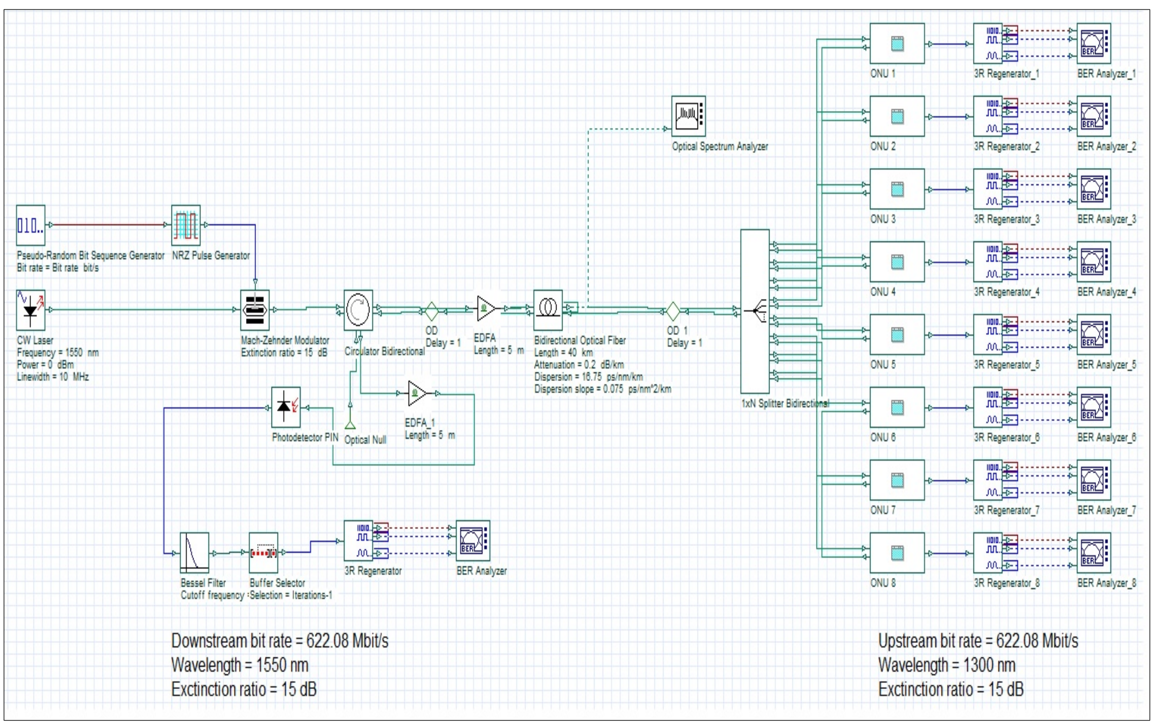



Figure 4.1: Simulation set up

| Side | Component | Traffic Direction | Parameter | Value |
|---|---|---|---|---|
| **Transmitter** | NRZ and RZ Pulse Generators | **Both** | Amplitude | *1 a.u.* |
| | | | Rise Time | *0.05 bit* |
| | | | Fall Time | *0.05 bit* |
| | CW Laser | **Downstream** | Frequency | *1550 nm* |
| | | | Power | *0 dBm* |
| | | | Linewidth | *10 MHz* |
| | | **Upstream** | Frequency | *1300 nm* |
| | | | Power | *0 dBm* |
| | | | Linewidth | *10 MHz* |
| | Mach-Zehnder | **Both** | Extinction Ratio | *15 dB* |
| **Channel** | Single Optical Fiber | **Both** | Length | *20, 40, 60, 80, 100, 120, 140, and 150 km* |
| | | | Attenuation | *0.25 dB/km* |
| | | | Dispersion | *16.75 ps/nm/km* |
| | Optical Splitter | **Both** | Number of Users | *8, 16, and 32* |
| **Receiver** | PIN Photodetector | **Both** | Responsivity | *1 A/W* |
| | | | Dark Current | *10 nA* |
| | Bessel Filter | | Cutoff Frequency | *0.75*Bit rate Hz* |

Table 4.1: BPON optical simulation parametric values

Figure 4.2 shows what is inside the subsystems, which are the ONUs. The subsystems or ONUs are the elements that are responsible for converting the optical signals to electrical signals in the downstream traffic direction. The entire

ONUs linked to the users include a distinct transmitter in order to modulate user data onto laser beams and transmit the data to the optical splitter. The optical splitter acts as an optical combiner in the upstream traffic direction. The combined signal collected from different users is transmitted to the OLT side in the central office in order to analyze it by using the BER analyzer.

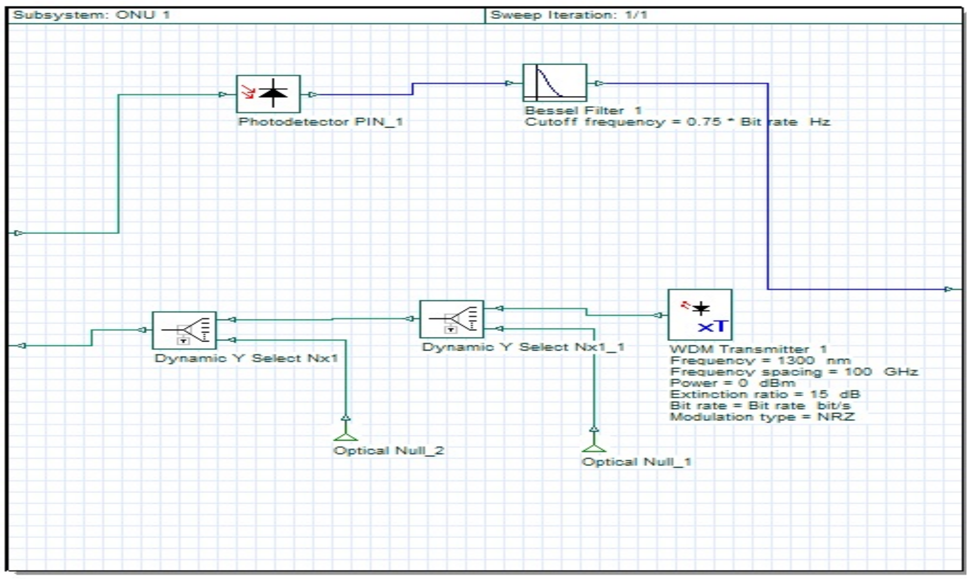



Figure 4.2: Inside the ONU

The structure of bidirectional PON for 32 users utilizing single optical fibers depends on the optical circulator. The optical circulator is utilized for two reasons: isolating optical signals of upstream and downstream traffic and recognizing bidirectional transmission in single fiber. Upstream is utilized in order to collect data from users, and downstream is utilized in order to broadcast multiservice such as data, voice, and video services to users.

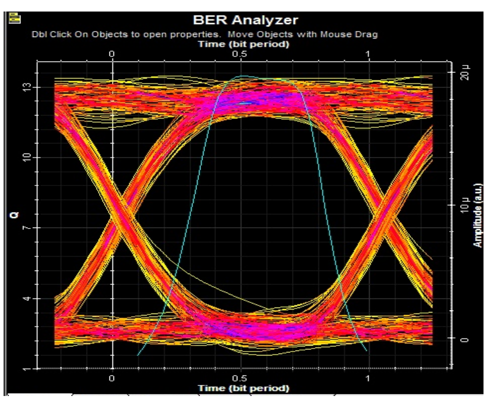
In the simulation shown in Figure 4.1, the properties of the bidirectional circulator used are wavelength dependent isolation, insertion, and return loss. In downstream traffic direction, an EDFA has been placed after the optical bidirectional circulator and before the single bidirectional optical fiber in order to improve the performance of the passive optical network.

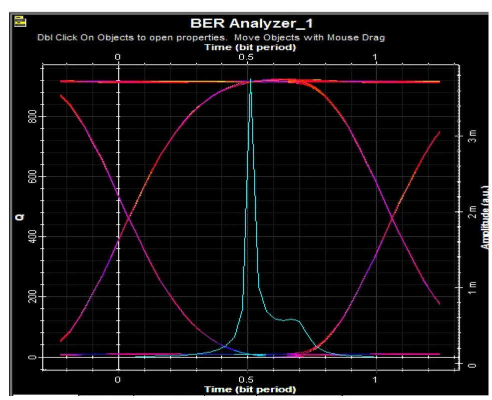
In order to create optical signal delay, a delay element has been placed in the transmission network. In order to have a delay, a NULL signal is transmitted to the output port. PINs are utilized in order to convert the optical signal transmitted through the fiber into an electric signal. After that, the electric signals that are converted by the PINs go to the low-pass Bessel filters and then 3R regenerators. It is possible to recover the original bits and electric signals by utilizing the 3R generator. The three terminals outputted from the 3R regenerators are connected to the BER analyzer in order to test the signal transmitted.

The results have been made based on five important factors: the number of users, coding technique, optical fiber length, extinction ratio, and dispersion. Optical fiber length has been selected to differ from 20km to 150km. NRZ and RZ are two different coding techniques that have been used. In this paper, a number of users have been chosen according to the standard optical splitter for the BPON architecture, which is 32 users or less. Therefore, 8, 16, and 32 users have been chosen. The extinction ratio has been chosen to be varied from 5dB to 30dB. The value of the dispersion in the optical fiber, has been chosen to be varied from 7ps/nm/km to 17ps/nm/km. Eye diagrams have been obtained to analyze the performance of the signal in both the downstream and upstream traffic directions. Maximum Q factor, minimum bit error rate, and eye height are three parameters have been tested in this proposed research. These three parameters are important to analyze the performance of the received signal in the optical communication system.

In order to test the BPON system, three parameters that are maximum Q factor, minimum bit error rate, and eye height have to be tested. Maximum Q factor and the signal-to-noise ratio (SNR) are two parameters that are proportional to each other [*19*]. The maximum Q factor is not a dimension quantity that analyzes the quality of the signal. Minimum bit error rate is also not a dimension quantity that analyzes the performance of the signal. Minimum bit error rate can be described as the ratio of the number of bit errors realized in the receiver side to the original number of bits transmitted in the transmitter side [*19*]. Depending on the definition of the minimum bit error rate, the ideal case is when the ratio becomes 0 and the worst case is when the ratio becomes 1. The entirety of sent bits is transmitted with no errors when the ratio results in 0, while the entirety of sent bits are full of errors when the ratio results in 1. The distortion of the signal is realized by the height of the eye. Less distortion has happened to the signal when the height of the signal is largest [*10*].

### 4.3 Results and Discussion

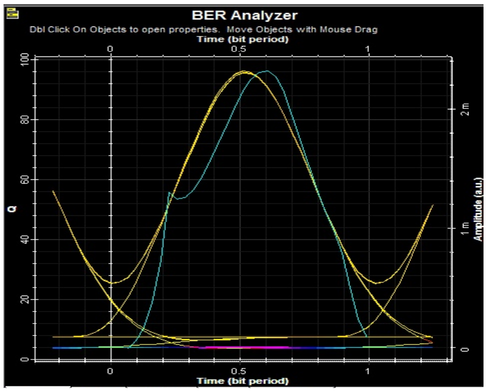


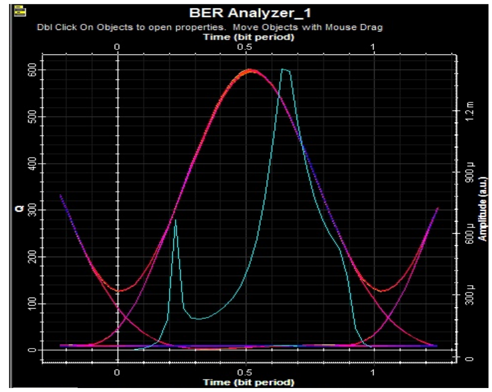

(a) (b)

Figure 4.3: Eye diagrams for 8 users with 20km fiber length using NRZ technique. (a) Upstream (b) Downstream

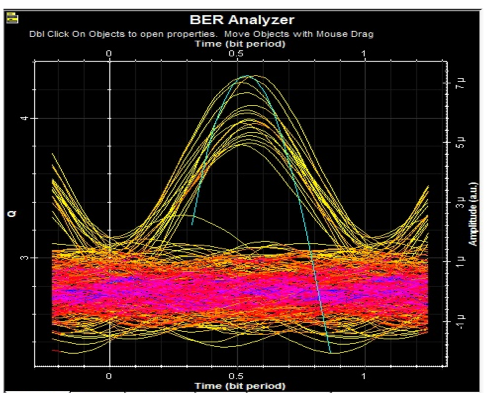
An eye diagram for 8 users using NRZ coding technique and 20km optical fiber distance for both downstream and upstream traffic directions is shown in Figure 4.3.



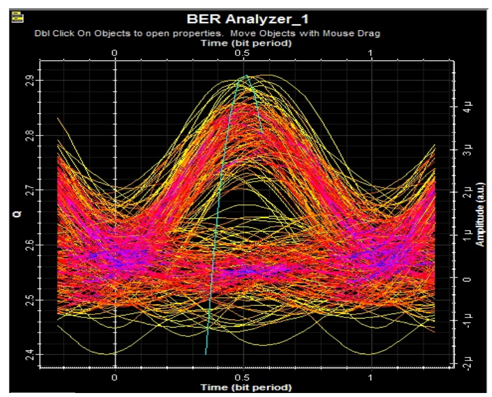

(a)




(b)




(c)




(d)

Figure 4.4: 32 users using RZ technique. (a) Upstream 20km fiber length. (b) Downstream 20km fiber length. (c) Upstream 150km fiber length. (d) Downstream 150km fiber length.

In order to compare between the eye diagram with the lowest dispersion and another eye diagram with maximum dispersion, Figure 4.4 has been provided. The eye diagrams provided are 32 users using the RZ technique for both upstream and downstream traffic directions running 20km and 150km distance. When the signal runs for 20km, which is short distance, the signal is very pure and undistorted.

However, when the signal runs 150km, which is long distance, the signal is very ambiguous and unclear, which is due to the distortion.

### 4.3.1 Different Users with Different Coding Techniques

In this section, a comparison is made between three different sets of users which are 8, 16, and 32 users with the use of two kinds of coding techniques: NRZ and RZ. This comparison is made according to three parameters, which are maximum Q factor, minimum BER, and eye height in both the downstream and the upstream traffic directions. Modulation techniques are essential components in order to analyze the performance of the optical network regarding channel capacity. NRZ and RZ are two kinds of coding technique modulation formats that can be utilized in the BPON system.

#### *4.3.1.1 Maximum Q Factor*

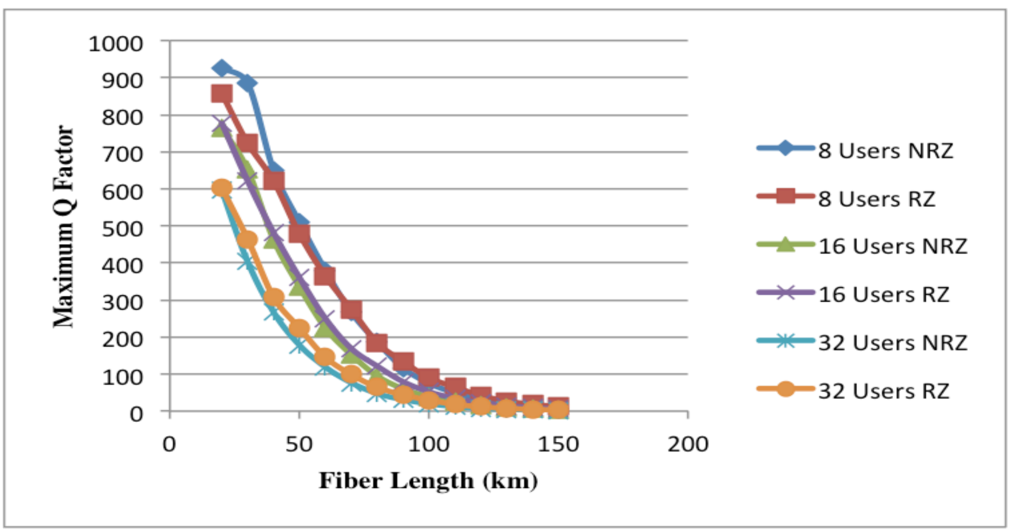



Figure 4.5: Maximum Q factor for the downstream for different users and coding techniques

RZ coding technique suffers more than NRZ coding technique and which can result from the dispersion because of the short pulse width in both the downstream and upstream traffic directions as shown in Figures 4.5 and 4.6. It is obvious from the Figures 4.5 and 4.6 that the RZ coding technique achieves poorer results than the NRZ coding technique. Because NRZ coding technique demands less bandwidth than RZ coding technique, NRZ coding technique has been used widely.

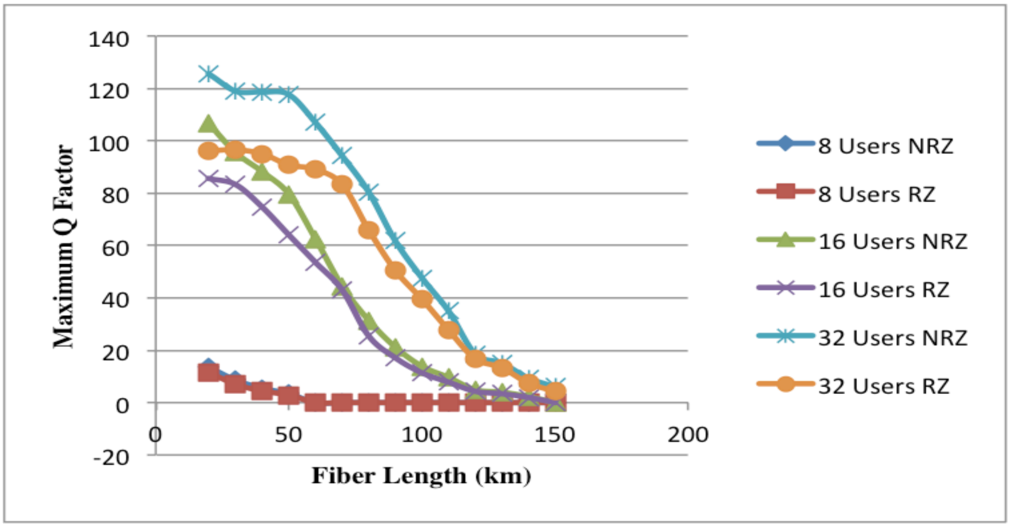



Figure 4.6: Maximum Q factor for the upstream for different users and coding techniques

#### *4.3.1.2 Minimum BER*

The minimum BER results are not clear in the graphs since the values obtained are very small. Therefore, the obtained results for the minimum BER for both the downstream and upstream traffic directions are shown in Tables 4.2 and 4.3. In the downstream traffic direction, as the fiber length increased, the bit error rate increases. That is because the dispersion increases as the optical fiber length increases as show in Table 4.2. As can be seen in Table 4.3, which is the minimum BER of the upstream traffic direction, as the number of users increases, the minimum BER decreases. Therefore, as the number of users increase, the performance of the system in the upstream direction increases as well.

| Fiber Length (km) | 8 Users NRZ | 8 Users RZ | 16 Users NRZ | 16 Users RZ | 32 Users NRZ | 32 Users RZ |
|---|---|---|---|---|---|---|
| 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 0 | 0 | 0 | 0 | 0 | 0 |
| 60 | 0 | 0 | 0 | 0 | 0 | 0 |
| 70 | 0 | 0 | 0 | 0 | 0 | 0 |
| 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 90 | 0 | 0 | 0 | 0 | 1.60E-212 | 0 |
| 100 | 0 | 0 | 0 | 0 | 2.58E-88 | 3.21E-195 |
| 110 | 0 | 0 | 3.51E-134 | 1.04E-264 | 4.17E-36 | 1.55E-74 |
| 120 | 1.81E-210 | 0 | 8.81E-57 | 2.42E-118 | 1.05E-14 | 3.50E-32 |
| 130 | 9.12E-89 | 1.17E-162 | 1.66E-22 | 1.27E-49 | 6.49E-07 | 1.85E-14 |
| 140 | 1.62E-34 | 1.06E-75 | 1.11E-09 | 1.01E-21 | 7.85E-04 | 7.96E-07 |
| 150 | 6.19E-15 | 7.43E-33 | 1.45E-05 | 1.26E-09 | 1.00 | 1.80E-03 |

Table 4.2: Minimum BER for the downstream for different users and coding techniques

| Fiber Length (km) | 8 Users NRZ | 8 Users RZ | 16 Users NRZ | 16 Users RZ | 32 Users NRZ | 32 Users RZ |
|---|---|---|---|---|---|---|
| 20 | 1.11E-41 | 4.72E-31 | 0 | 0 | 0 | 0 |
| 30 | 3.87E-18 | 1.17E-12 | 0 | 0 | 0 | 0 |
| 40 | 2.31E-08 | 4.86E-06 | 0 | 0 | 0 | 0 |
| 50 | 3.06E-04 | 1.93E-03 | 0 | 0 | 0 | 0 |
| 60 | 1.00 | 1.00 | 0 | 0 | 0 | 0 |
| 70 | 1.00 | 1.00 | 0 | 0 | 0 | 0 |
| 80 | 1.00 | 1.00 | 9.07E-217 | 1.49E-143 | 0 | 0 |
| 90 | 1.00 | 1.00 | 3.83E-100 | 4.96E-66 | 0 | 0 |
| 100 | 1.00 | 1.00 | 2.84E-44 | 1.78E-30 | 0 | 0 |
| 110 | 1.00 | 1.00 | 1.58E-22 | 1.54E-15 | 2.11E-268 | 7.71E-170 |
| 120 | 1.00 | 1.00 | 1.87E-07 | 3.87E-06 | 5.07E-78 | 1.10E-63 |
| 130 | 1.00 | 1.00 | 1.87E-05 | 2.01E-04 | 4.40E-52 | 5.12E-41 |
| 140 | 1.00 | 1.00 | 4.53E-03 | 1.10E-02 | 2.22E-21 | 2.95E-14 |
| 150 | 1.00 | 1.00 | 1.00 | 1.00 | 4.45E-10 | 3.71E-06 |

Table 4.3: Minimum BER for the upstream for different users and coding techniques

#### *4.3.1.3 Eye Height*

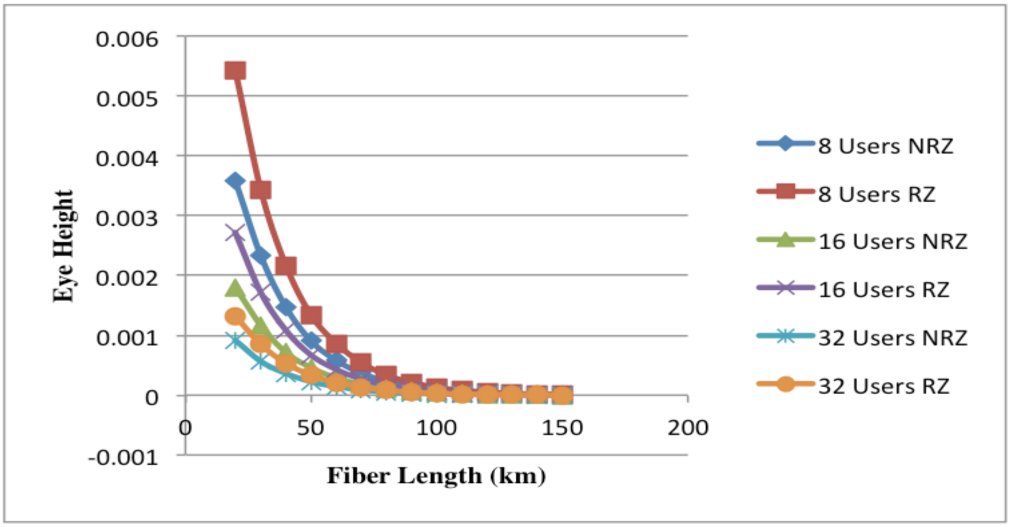



Figure 4.7: Eye height for the downstream for different users and coding techniques

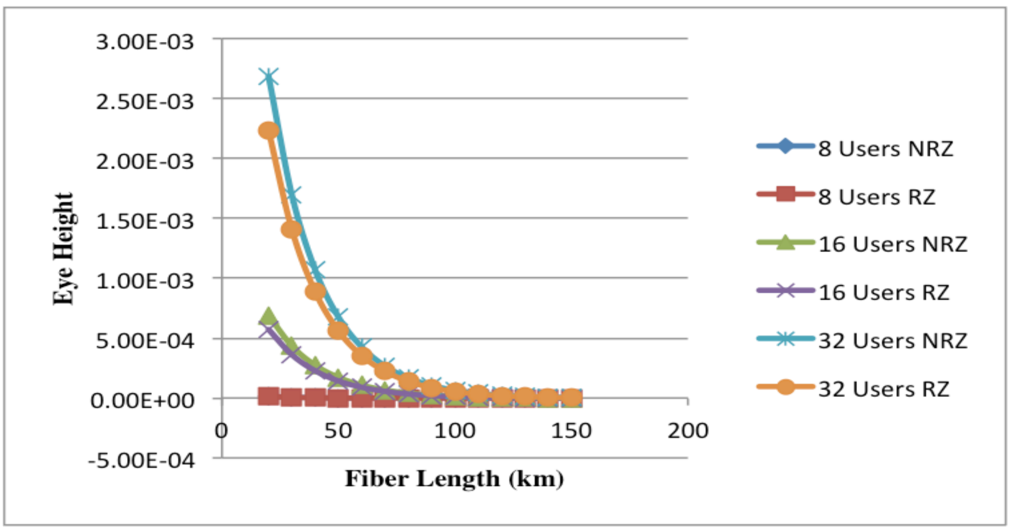



Figure 4.8: Eye height for the upstream for different users and coding techniques

As can be seen from Figures 4.7 and 4.8 for both downstream and upstream traffic directions, eye height decreases exponentially as fiber length increases. In the case of eye height, the performance when having the RZ coding technique is better than the performance when having the NRZ coding technique for the downstream traffic direction. However, in the upstream traffic direction, the performance of the NRZ coding technique is better than the RZ coding technique.

### 4.3.2 Extinction Ratio

Extinction ratio is a parameter that characterizes the depth of the modulation in an optical signal. The extinction ratio can be defined as the ratio of the power in the one state to the zero state. It is popular to have the extinction ratio in dB. Results obtained in the extinction ratio section are on the basis of bidirectional BPON for 16 users with NRZ coding technique.

#### *4.3.2.1 Maximum Q Factor*

As expected, as the extinction ratio increases, the maximum Q factor increases in both the downstream and upstream traffic directions as shown in both Figures 4.9 and 4.10. In the case of the downstream traffic direction, the extinction ratio decreases exponentially. However, in the upstream traffic direction, the extinction ratio decreases until the optical fiber reaches 60km, after which the optical signal disappears.

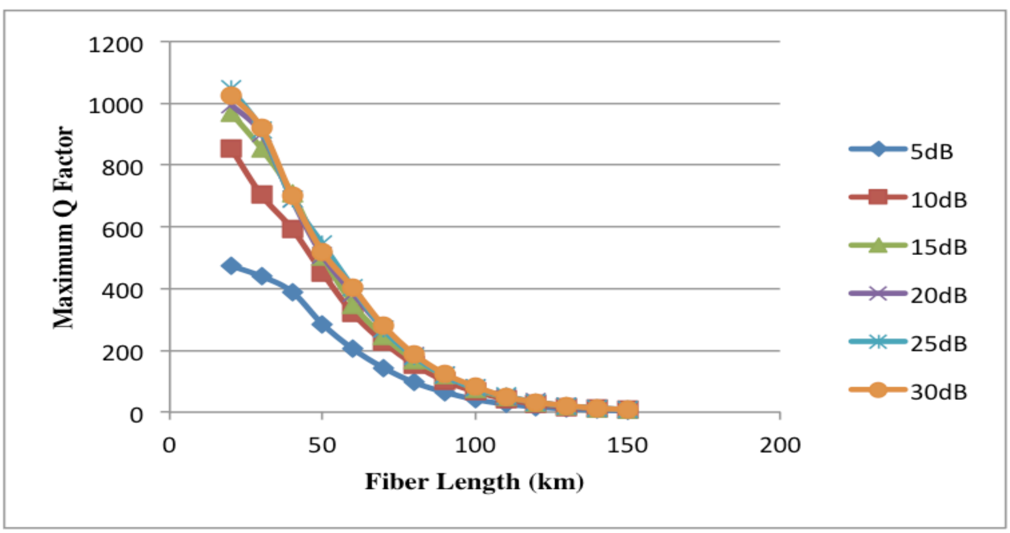



Figure 4.9: Maximum Q factor for the downstream for different extinction ratio values

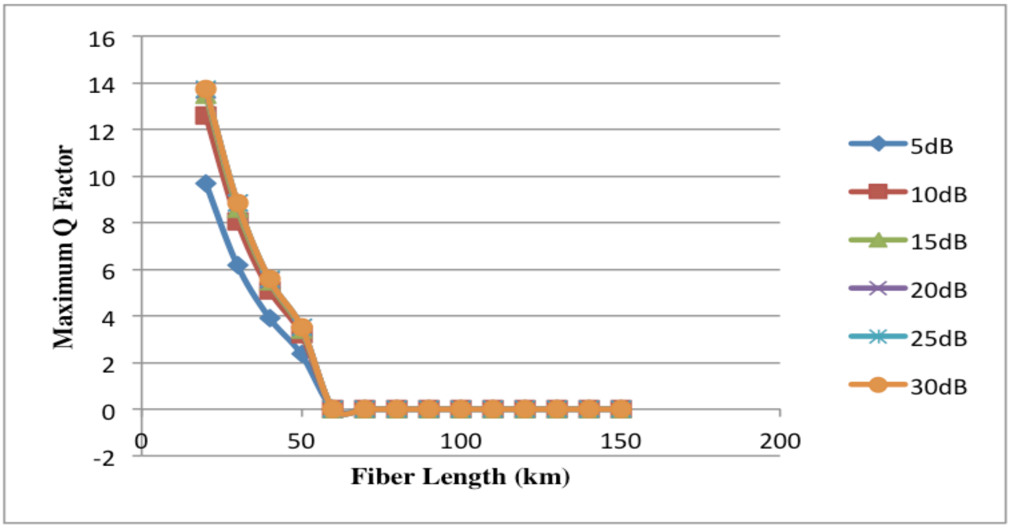



Figure 4.10: Maximum Q factor for the upstream for different extinction ratio values

#### *4.3.2.2 Minimum BER*

| Fiber Length | 5dB | 10dB | 15dB | 20dB | 25dB | 30dB |
|---|---|---|---|---|---|---|
| 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 0 | 0 | 0 | 0 | 0 | 0 |
| 60 | 0 | 0 | 0 | 0 | 0 | 0 |
| 70 | 0 | 0 | 0 | 0 | 0 | 0 |
| 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 90 | 0 | 0 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0 | 0 | 0 |
| 110 | 9.77E-153 | 0 | 0 | 0 | 0 | 0 |
| 120 | 3.57E-64 | 1.74E-151 | 3.78E-216 | 2.85E-236 | 4.04E-232 | 6.38E-234 |
| 130 | 4.89E-27 | 2.00E-67 | 2.82E-85 | 3.74E-94 | 7.22E-94 | 2.45E-99 |
| 140 | 6.21E-12 | 5.76E-28 | 5.07E-36 | 1.92E-37 | 2.24E-41 | 5.71E-40 |
| 150 | 1.07E-05 | 3.21E-12 | 3.19E-15 | 2.21E-17 | 5.86E-17 | 6.38E-17 |

Table 4.4: Minimum BER for the downstream for different extinction ratio values

The minimum BER for the downstream traffic direction shown in Table 4.4 shows ultimate performance until 100km fiber length. The performance of the optical signal is acceptable until 140km fiber length. However, the performance of the optical signal is not acceptable when the fiber length reaches 150km. In the upstream traffic direction, it is obvious that the bits in the optical signal are totally reversed when the fiber length reaches 60km and more as shown in Table 4.5.

| Fiber Length | 5dB | 10dB | 15dB | 20dB | 25dB | 30dB |
|---|---|---|---|---|---|---|
| 20 | 1.76E-22 | 8.19E-37 | 1.11E-41 | 4.88E-43 | 2.50E-43 | 2.43E-43 |
| 30 | 3.44E-10 | 3.90E-16 | 3.87E-18 | 5.01E-19 | 3.82E-19 | 3.80E-19 |
| 40 | 4.47E-05 | 1.55E-07 | 2.31E-08 | 1.36E-08 | 1.22E-08 | 1.21E-08 |
| 50 | 9.26E-03 | 6.62E-04 | 3.06E-04 | 2.10E-04 | 2.01E-04 | 2.01E-04 |
| 60 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 70 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 80 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 90 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 110 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 120 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 130 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 140 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 150 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Table 4.5: Minimum BER for the upstream for different extinction ratio values

#### *4.3.2.3 Eye Height*

Similar to what happened in the last section, the eye height in the downstream traffic direction decreases exponentially as the fiber length increases. However, in the case of the upstream traffic direction, the eye height disappeared when the fiber length reached 60km. The maximum Q factor of the BPON system is largest when the extinction ratio has the largest value, which is 30dB. On the other hand, the maximum Q factor is lowest when the value of the extinction ratio is lowest, which is 5dB.

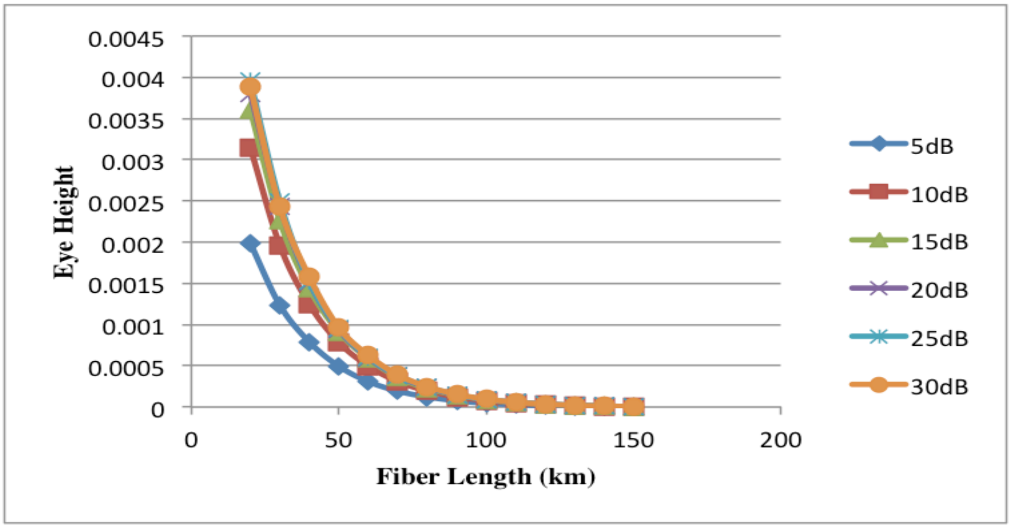



Figure 4.11: Eye height for the downstream for different extinction ratio values

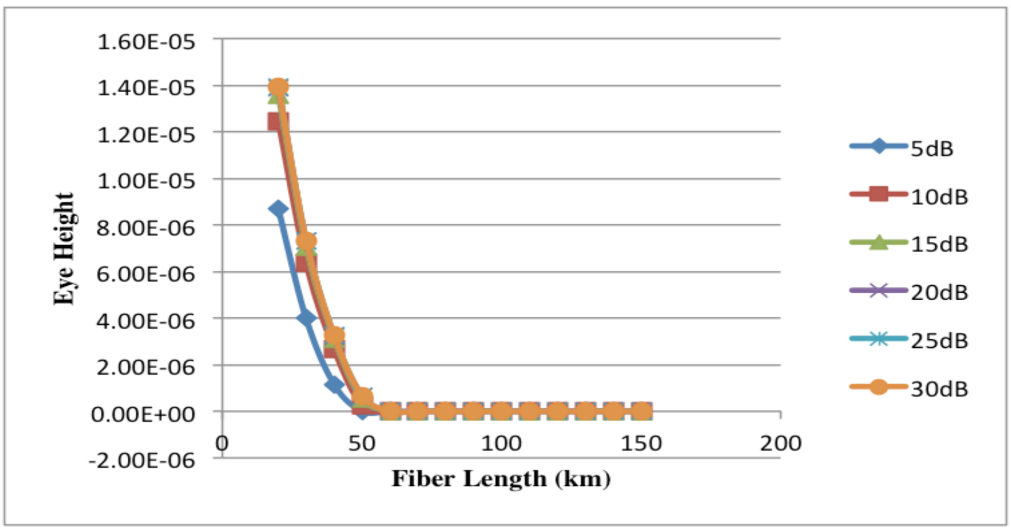



Figure 4.12: Eye height for the upstream for different extinction ratio values

### 4.3.3 Fiber Dispersion

Results obtained in the fiber's dispersion section are on the basis of bidirectional BPON for 8 users with NRZ coding technique. In this section, the effect of the fiber dispersion on the performance of the BPON system is discussed. The performance of the BPON system has been tested depending on three parameters that are the maximum Q factor, minimum bit error rate, and eye height.

#### *4.3.3.1 Maximum Q Factor*

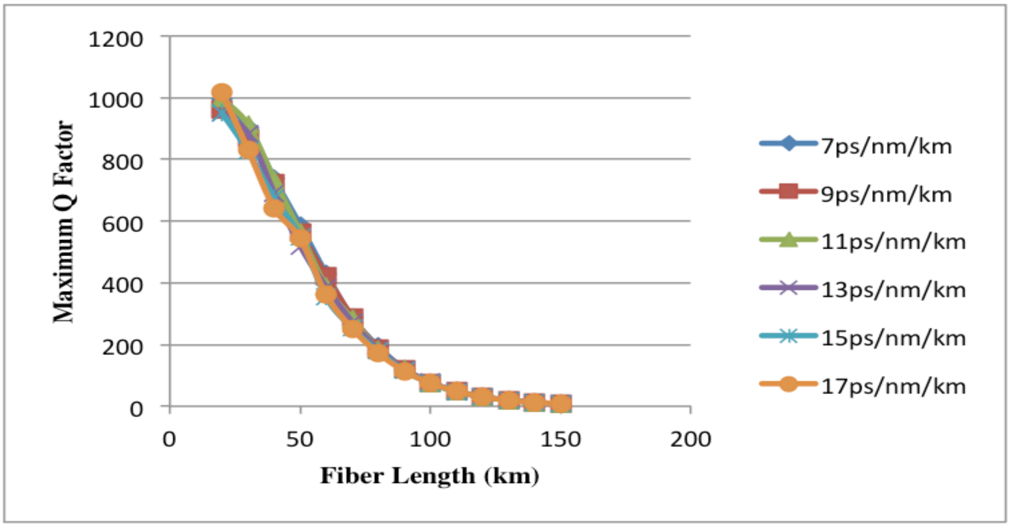



Figure 4.13: Maximum Q factor for the downstream for different fiber dispersion values

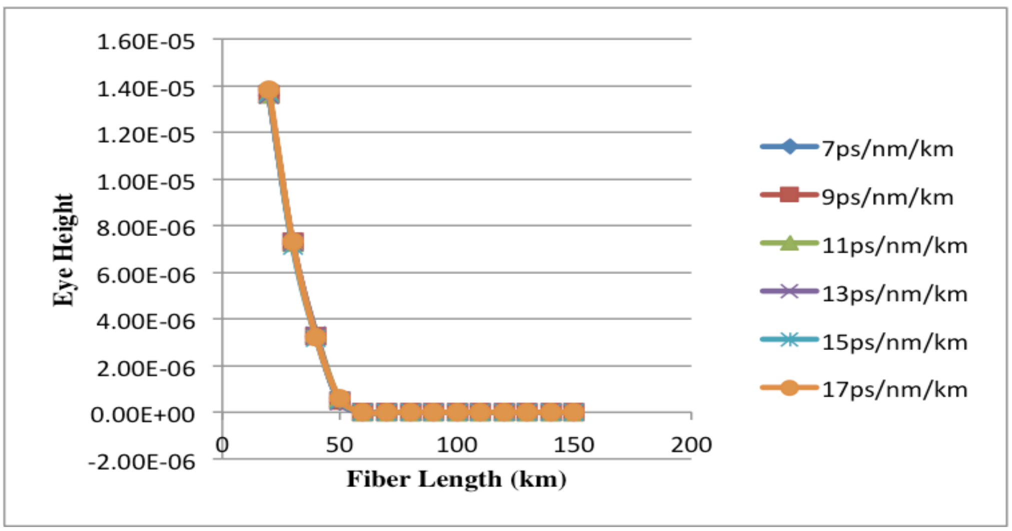



Figure 4.14: Maximum Q factor for the upstream for different fiber dispersion values

From the results that have been obtained, in both the downstream and upstream traffic directions, as the value of the bidirectional optical fiber increases, the maximum Q factor decreases. It is obvious in the downstream traffic in Figure 4.13 more than it is in the upstream traffic in Figure 4.14. However, increasing the dispersion value of the bidirectional optical fiber in the ranges chosen (from 7ps/nm/km to 17ps/nm/km) does not give a clear picture of the decrease in the performance of the system.

#### *4.3.3.2 Minimum BER*

| Fiber Length | 7 ps/nm/km | 9 ps/nm/km | 11 ps/nm/km | 13 ps/nm/km | 15 ps/nm/km | 17 ps/nm/km |
|---|---|---|---|---|---|---|
| 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 0 | 0 | 0 | 0 | 0 | 0 |
| 60 | 0 | 0 | 0 | 0 | 0 | 0 |
| 70 | 0 | 0 | 0 | 0 | 0 | 0 |
| 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 90 | 0 | 0 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0 | 0 | 0 |
| 110 | 0 | 0 | 0 | 0 | 0 | 0 |
| 120 | 1.41E-212 | 1.48E-209 | 3.42E-207 | 1.41E-215 | 6.61E-214 | 6.09E-206 |
| 130 | 8.40E-89 | 1.11E-85 | 4.93E-86 | 3.99E-89 | 2.74E-85 | 2.29E-84 |
| 140 | 1.58E-34 | 6.32E-36 | 1.75E-36 | 1.69E-37 | 1.97E-34 | 8.00E-36 |
| 150 | 6.69E-15 | 4.87E-15 | 3.92E-15 | 2.15E-14 | 5.81E-16 | 1.40E-15 |

Table 4.6: Minimum BER for the downstream for different fiber dispersion values

| Fiber Length | 7 ps/nm/km | 9 ps/nm/km | 11 ps/nm/km | 13 ps/nm/km | 15 ps/nm/km | 17 ps/nm/km |
|---|---|---|---|---|---|---|
| 20 | 2.29E-42 | 5.22E-43 | 4.01E-43 | 1.77E-42 | 1.15E-42 | 2.67E-44 |
| 30 | 3.14E-18 | 1.00E-18 | 2.37E-18 | 1.62E-18 | 5.00E-18 | 1.50E-18 |
| 40 | 1.11E-08 | 1.02E-08 | 6.10E-09 | 7.01E-09 | 1.71E-08 | 1.24E-08 |
| 50 | 3.98E-04 | 3.54E-04 | 2.73E-04 | 3.71E-04 | 3.36E-04 | 2.77E-04 |
| 60 | 1.00 | 1.00 | 1.52E-02 | 1.29E-02 | 1.00 | 1.26E-02 |
| 70 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 80 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 90 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 100 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 110 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 120 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 130 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 140 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 150 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Table 4.7: Minimum BER for the upstream for different fiber dispersion values

As can be seen from Table 4.6, the minimum BER is in its ultimate performance until the fiber length reaches 110km. Then, the performance of the BPON system starts to decrease. As can be seen from both Table 4.6 and 4.7, the minimum BER does not clearly show that it increases as the fiber length increases.

#### *4.3.3.3 Eye Height*

The same thing can be applied to the eye height, as it can obviously be seen from Figure 4.18 and 4.19 that the curves of different values of dispersion are approximately the same. Also, as shown previously, the performance of the system decreases exponentially in the downstream traffic direction. However, in the upstream traffic direction, the performance of the BPON system decreased suddenly when the fiber length reached 60km.

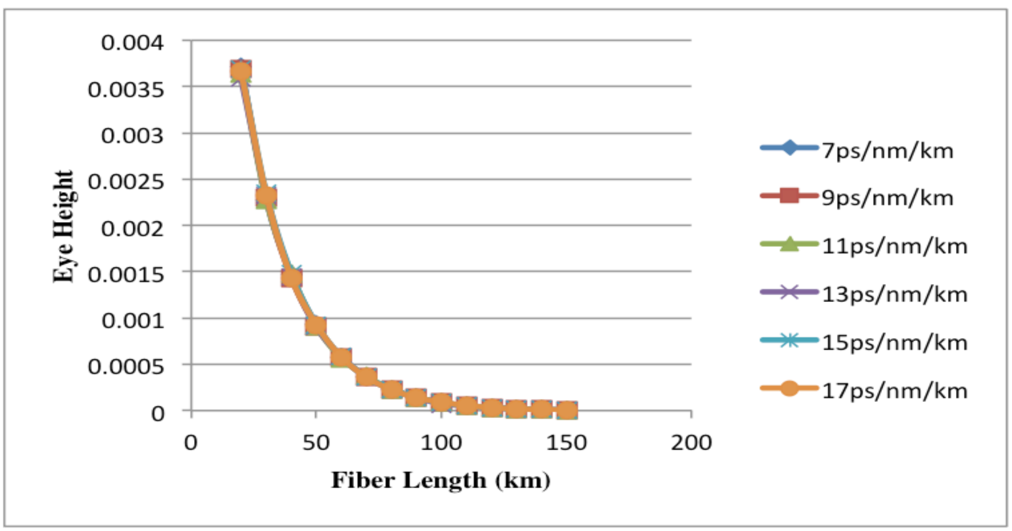



Figure 4.15: Eye height for the downstream for different fiber dispersion values

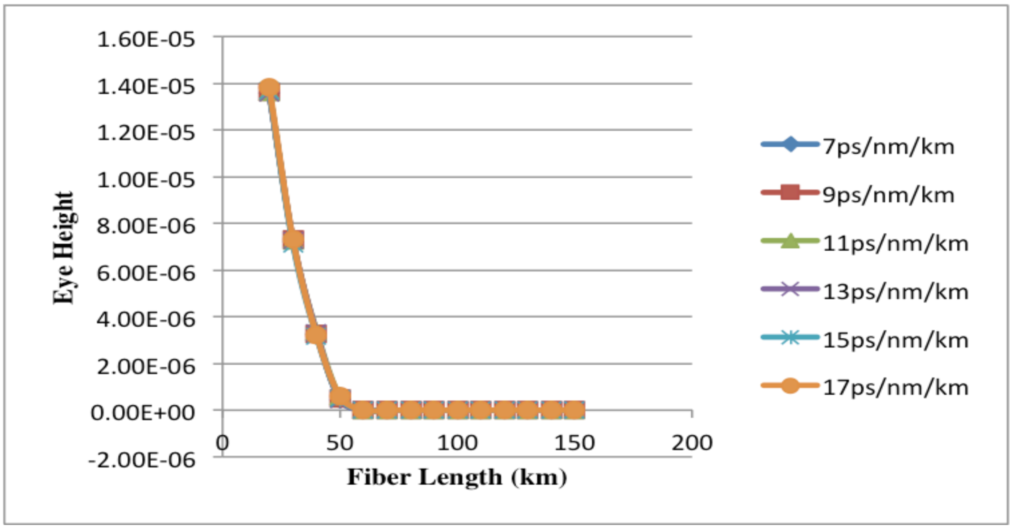



Figure 4.16: Eye height for the upstream for different fiber dispersion values

# Chapter Five: Conclusion and Future Work

## 5.1 Conclusion

In this proposed research, the performance of the bidirectional BPON in both downstream and upstream traffic by utilizing EDFA have been analyzed. The system has been studied according to the number of users, coding techniques, fiber length, extinction ratio, and fiber dispersion. The standard distance of the BPON architecture is 20km as shown previously in section 3.1. However, we were able to extend the distance from 20km to approximately 150km under certain conditions.

From the results obtained in this paper, it has been observed that when the number of users and fiber length have been increased, bit error rate is increased as well, but the maximum Q factor and eye height are decreased due to dispersion. From the simulation and the results done in this research, when using the NRZ coding technique in the BPON system, the BPON has better performance in comparison to when the RZ coding technique is used. This is because of two factors. The NRZ coding technique demands less bandwidth requirement, and it is more tolerable to optical dispersion than the RZ coding technique. At short fiber length distances and for less number of users, the BPON system has a higher acceptable maximum Q factor, minimum bit error rate, and eye height.

When comparing today's networks with future networks, the main characteristics of future networks will be the rise in bandwidth needed to handle the network and the optical networking that will be demanded in all parts of the architecture. As a result of these two main features, these have an effect on the necessities for future optical mechanisms and technology.

## 5.2 Future Work

As for the future work, I am thinking of having a way of reducing the cost of the components used in the design and increasing the performance of the network. For example, if an APD component were used, which is relatively with high price, instead of PIN component the performance of the designed BPON system will increase.

The maximum standard of BPON in the downstream traffic direction is 1244Mb/s and in the upstream is 622Mb/s. It is better to have a data rate of higher amounts. The standard maximum users that the BPON can serve are 32. It is better to have a way to increase the number of users.

In conclusion, I will focus my effort to having BPON optical network with high performance and low cost. I will also find a way of having BPONs with a higher data rate in both the downstream and upstream traffic directions. Finally, I will find a solution to increase the number of users that the BPON can serve.

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## Appendix A: Journal Publications

***IOSR Journal of Engineering (IOSRJEN)***
*e-ISSN: 2250-3021, p-ISSN: 2278-8719, www.iosrjen.org*
*Volume 04, Issue 02 (February 2014), //V6// PP 91-97*

# Analysis of Transmitting 40Gb/s CWDM Based on Extinction Value and Fiber Length Using EDFA

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***Abstract: -*** It is difficult in optical communication systems to predict the final signal at the customer side because of using various components and the effect of many features. Simulation helps to analyze and expect the performance before any actual hardware is done. In the proposed research, Optisystem 12$^{th}$ version software is used in order to analyze transmitting 40Gb/s, 10Gb/s for each channel, in four channels of coarse wavelength division multiplexing (CWDM) from the transmitter to the receiver based on extinction ratio and the distance of the optical fiber until 100km. An Erbium-Doped Fiber Amplifier (EDFA) is used for long distances. The objective of the simulation is to certify that the received signals are not affected by the noise and attenuation so they are undamaged and in good condition by using bit error rate (BER) analyzer. From the simulation obtained, maximum Q factor, eye height, and threshold decreased as the fiber length increased, and as the value of the extinction ratio increased, the eye height increased but threshold decreased. The results of the CWDM are presented in this paper.

***Keywords: -*** *Bit Error Rate (BER), Coarse Wavelength Division Multiplexing (CWDM), Erbium-Doped Fiber Amplifier (EDFA),*

## I. INTRODUCTION

In these days, there is severe increase in the need for more bandwidth and is probably will continue for the feature. In order to fulfill this need, telecommunication companies have to investigate on increasing their channels' capacity with the lowest cost possible. Using wavelength division multiplexing (WDM) seems that it is one solution of reducing the cost. With WDM, number of wavelengths can be transmitted by one single fiber at the same time. Backing various transmission formats is another powerful tool that WDM has. Therefore, at any data rate, various formats signals can be transmitted independently and at the same time by the same fiber without the need for common signal structure by using separate wavelengths.

Coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM) are two types of WDM. CWDM is getting more attention in access, metro, and cable TV network because it can transmit more bandwidth with low cost comparing to DWDM. CWDM can carry wavelengths ranging between 1270 nm to 1610 nm with 20 nm channel spacing and requires inexpensive uncooled and direct modulated lasers result in low power consumption.

Although CWDM networks demand reduced cost compared to DWDM networks, repeaters or amplifiers are needed to expand the reach of the CWDM networks. Transmission at higher rates can be achieved when optical amplifiers such as erbium doped fiber amplifier (EDFA), semiconductor optical amplifier (SOA), Raman, or hybrid are used in the CWDM network. At the present time, a SOA is the exclusive suitable solution for amplification as a result of its simple design and reduced cost. To use SOAs in CWDM network, they should have adequate broad to deal with at least four channels. Different kinds of optical amplifiers are available in the market and depending on the application, specific one can be chosen. However, in terms of the price, the Raman amplifier is the most expensive one.

This paper studies mainly the affect of the extinction ratio and the fiber length on CWDM network with the use of EDFA. Optisystem software is used to simulate the CWDM link. By using bit error rate (BER) analyzer, different parameters such as maximum Q factor, minimum bit error rate, eye height, and threshold have been tested.

## II. DESCRIPTION OF THE OPTICAL DESIGN

In this optical design, 4-channel transmits 40Gb/s, each channel transmits 10Gb/s, is simulated with variety of extinction ratio and fiber lengths. When the length of the fiber reaches 40km, EDFA is used. The design consists of 4 transmitters and 4 receivers. In the transmitter side, return to zero (RZ) pulse generator is used in order to generate pseudo-random bit sequence (PRBS). Then, Mach-Zehnder is used to modulate the electric signal from RZ with continuous wave (CW) laser. An optical fiber with different distances is used to link between the transmitter and the receiver by using an EDFA for long distances. In the receiver side, Avalanche photodetectors (APDs) are used to convert the received optical signals to electrical signals. Then, These electrical signals are amplified using Trans-impedance Amplifier (TIAs) and the amplified signals are filtered through a second order low pass Gaussian filter. Bit Error Rate (BER) analyzers are used to realize the quality of the output signal for each channel. A schematic design of four channels CWDM is presented in Figure 1.

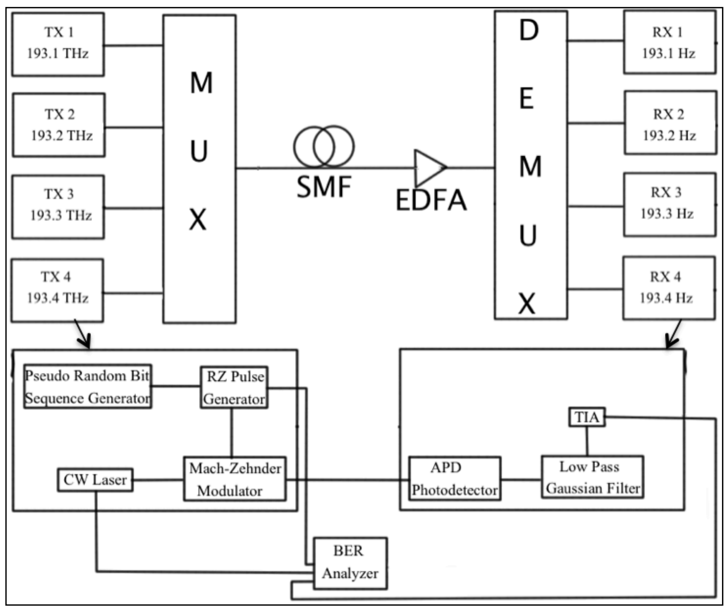



Fig1: Design schematic

## III. SIMULATION DESIGN

The simulation is performed by the use of Optisystem software. Optisystem gives the ability to the designer to change the design and the parameters to get better results. As shown in figure 2 the transmitter side consists of 4 transmitters at 193.1, 193.2, 193.3, and 193.4 THz with almost 100GHz spacing between the channels. Then, the media is WDM MUX works as CWDM, optical fiber with different lengths, EDFA, and WDM DEMUX. In the receiver side, photodetector APDs, low pass Gaussian filters, TIAs, and BER analyzers. The designed system is shown in Figure 2 and list of the parameters used are given in Table 1.

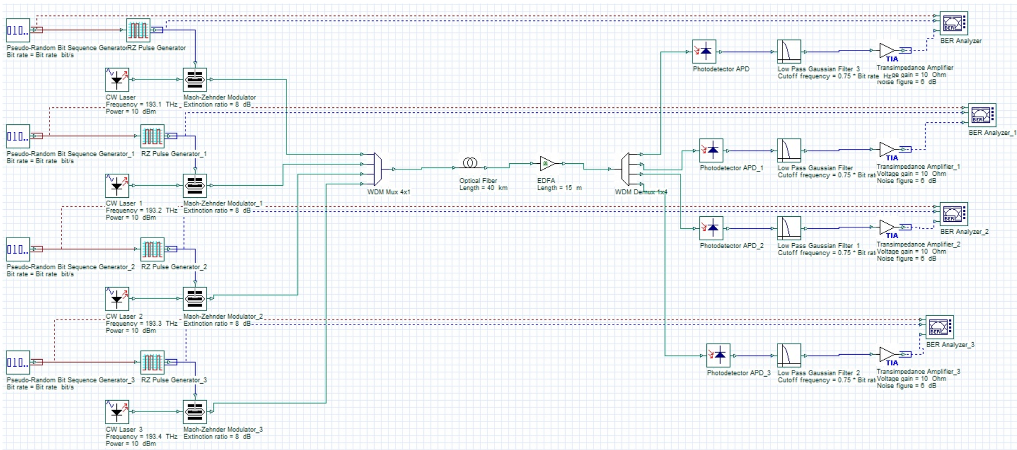



Fig2: Simulation Design

Table 1: Values of some components used in the simulation

| Side | Component | Parameter | Value |
|---|---|---|---|
| **Transmitter** | RZ Pulse Generator | Amplitude | 1 a.u. |
| | | Rise Time | 0.05 bit |
| | | Fall Time | 0.05 bit |
| | CW Laser | Frequency | 193.1, 193.2, 193.3, 193.4 THz |
| | | Power | 10 dBm |
| | | Linewidth | 10 MHz |
| | Mach-Zehnder | Extinction Ratio | 6, 6.5, 7, 7.5, 8 |
| **Channel** | Single Optical Fiber | Length | 5, 40, 60, 80, 100 km |
| | | Attenuation | 0.25 dB/km |
| | MUX | Filter Order | 2 |
| | DUMX | Filter Order | 2 |
| | EFDA | Length | 15 m |
| **Receiver** | APD Photodetector | Responsivity | 1 A/W |
| | | Dark Current | 10 nA |
| | Low Pass Gaussian Filter | Cutoff Frequency | 0.75*Bit rate |
| | TIA | Voltage Gain | 10 Ohm |

| | | | |
|---|---|---|---|
| | | Noise Figure | 6 dB |

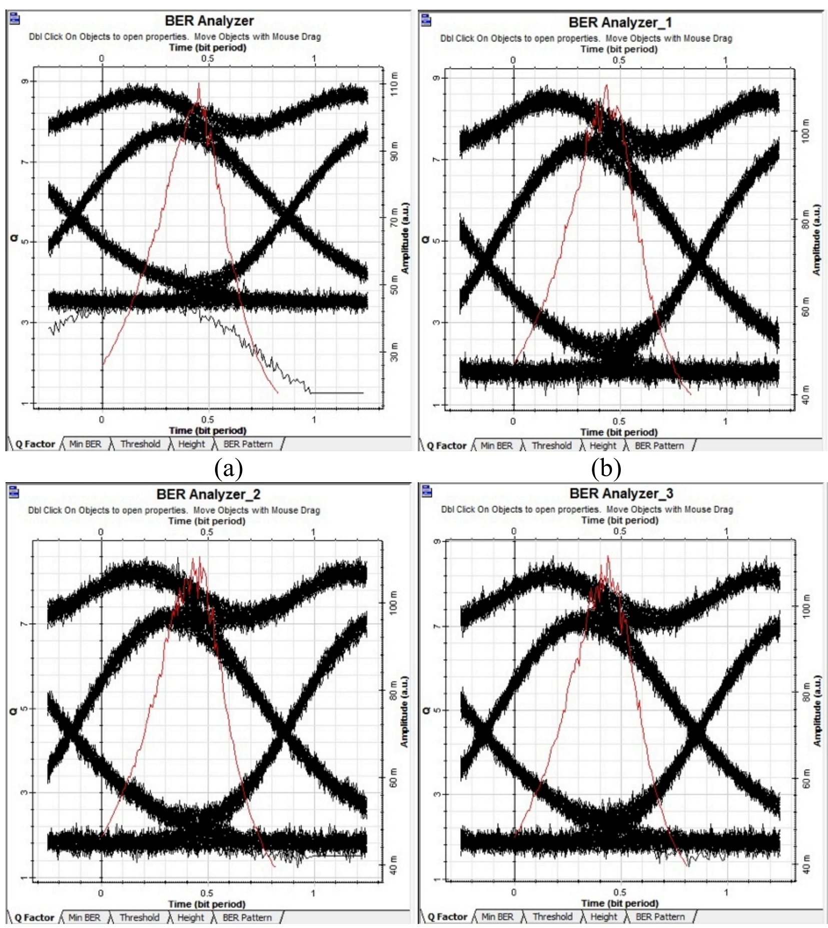
## IV. RESULTS AND DISCUSSION

### 4.1 Eye Diagram

Eye diagram or also known as eye pattern in telecommunication is an old technique used in order to evaluate the received signal. Totally opened eye pattern represents the lowest level of distortion. BER analyzers create eye diagrams by making a pseudorandom arrangement of 1s and 0s in a symmetric rate but in an arbitrary manner. In Optisystem, eye diagram, which can be found in the BER analyzer show various traces of modulated signal in order to create an eye diagram. Because of the shape of the pattern that looks as if it is an eye, it is called an eye diagram.

#### 4.1.1 Eye Diagram of 5km 6dB

The eye diagrams shown in figure 3 are obtained when the length of the fiber is 5km and extinction ratio is 6dB without using EDFA.



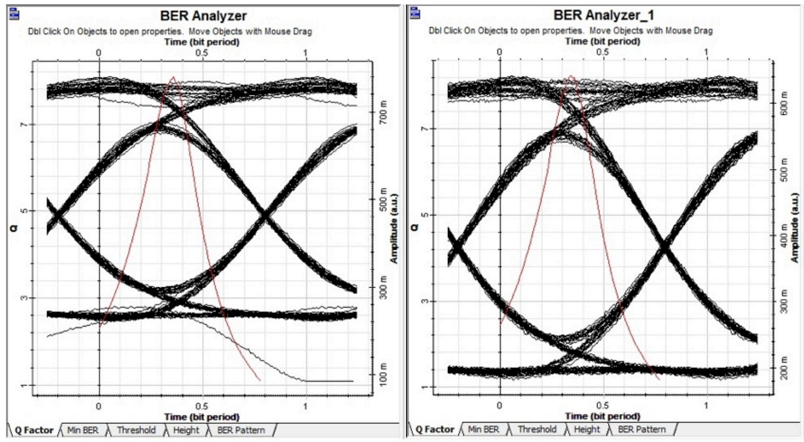

(a) (b)

(C) (d)

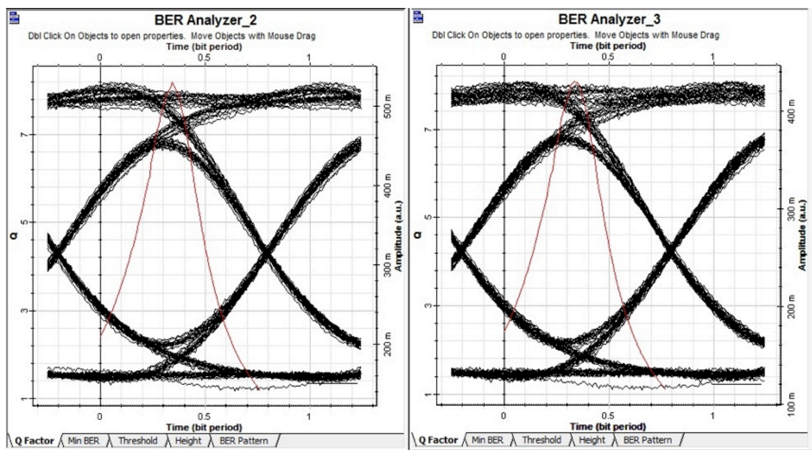
Fig3: Eye diagram of 5km 6dB. a) Eye diagram of channel 1. b) Eye diagram of channel 2. c) Eye diagram of channel 3. d) Eye diagram of channel 4.

#### 4.1.2 Eye Diagram of 40km 8dB Using EDFA

As shown in figure 4, eye diagrams are presented when 40km fiber length, 8dB extinction ratio, and EDFA are used.




(a) (b)




(C) (d)

Fig4: Eye diagram of 5km 6dB. a) Eye diagram of channel 1. b) Eye diagram of channel 2. c) Eye diagram of channel 3. d) Eye diagram of channel 4.

### 4.1 Effect of Varying Fiber Length with Using EDFA

Along the fiber, as the fiber length increased, the noise will be increased and the power will be lost as well. In this section, the effect of varying fiber length between 40km to 100km is tested. EDFA is used for this range of distances. The test is done by the use of BER analyzer, which can test maximum Q factor, minimum bit error rate, eye height, and threshold. Figure 4 shows the maximum Q factor versus fiber length ranges between 40km and 100km. The maximum Q factor decreased as the fiber length increased as shown in figure 5.

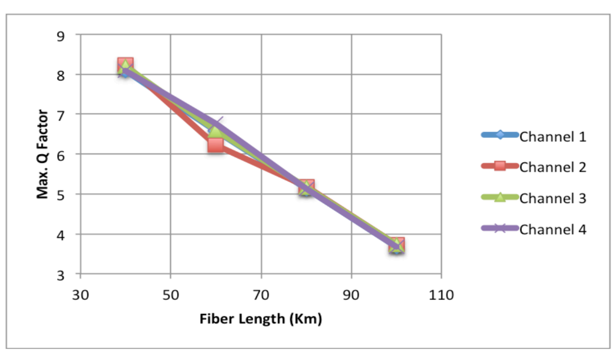



Fig5: Maximum Q factor vs. fiber length

The minimum bit error rate is almost constant between 40km and 80km. However, it suddenly increased when it reached 100km as can be obviously seen in figure 6.

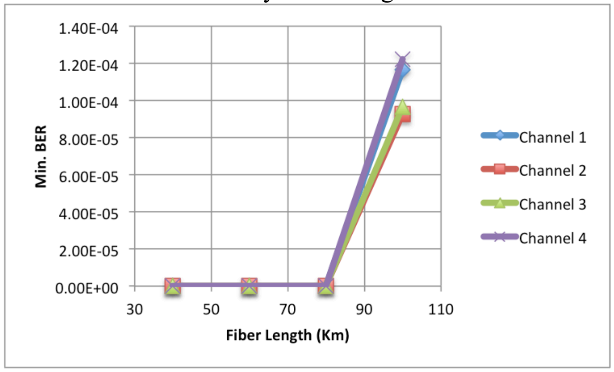



Fig6: Minimum BER vs. fiber length

As previously mentioned, totally opened eye pattern represents the lowest level of distortion. Figure 7 shows that the eye height decreased as the fiber length increased. That means, the distortion increased as the fiber length increased. As can be observed from figure 7, channel 1, which has larger wavelength, has larger eye height than channel 4, which has lower wavelength.

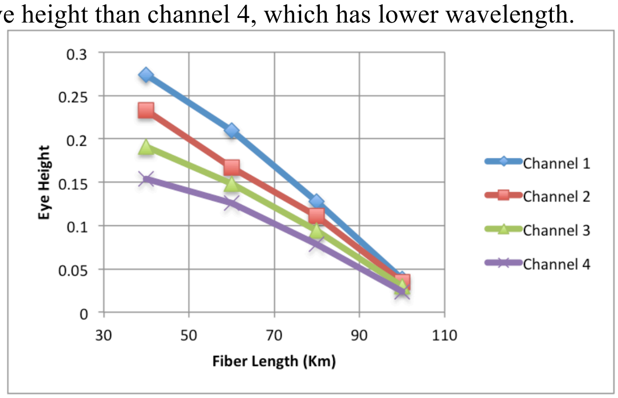



Fig7: Eye height vs. fiber length

Threshold decreased as the fiber length increased as shown in figure 8. As can be observed from the figure below first channel, which has higher wavelength has larger threshold than the fourth channel, which has lower one.

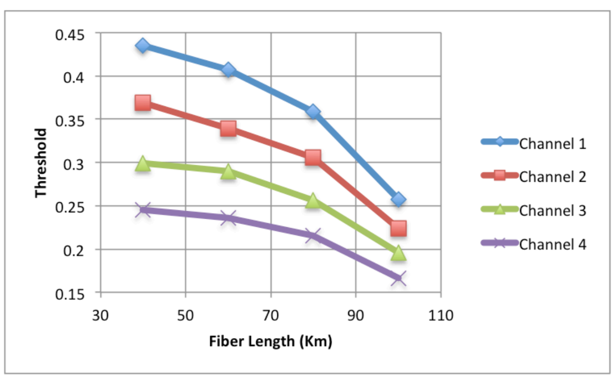



Fig8: Threshold vs. fiber length

**4.1 Effect of Extinction Ratio on 5km Fiber Length**

Extinction ratio is the proportion of the average energy in an addressed logic '1' to the average energy in an addressed logic '0'. Figure 9 shows maximum Q factor versus extinction ratio ranges between 6 and 8. It can be observed from figure 9 that channel 3 has the heighest maximum Q factor at extinction ratio of 7. However, the lowest maximum Q factor is happened for channel 4 at extinction ratio of 6.

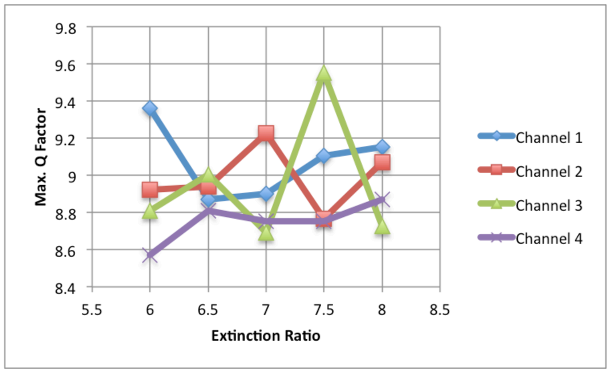



Fig9: Maximum Q factor vs. extinction ratio

From figure 10, the minimum BER is almost the same for all the channels along the extinction ratio ranging from 6 to 8. The minimum BER ranges between 6.27E-22 and 5.04E-18.

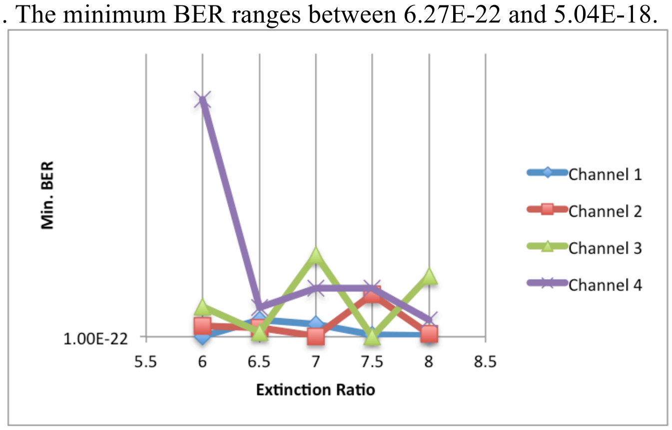



Fig10: Minimum BER vs. extinction ratio

As can be observed from figure 11, eye height increased as the extinction ratio increased. Therefore, to minimize the distortion, the extinction ratio should have larger value.

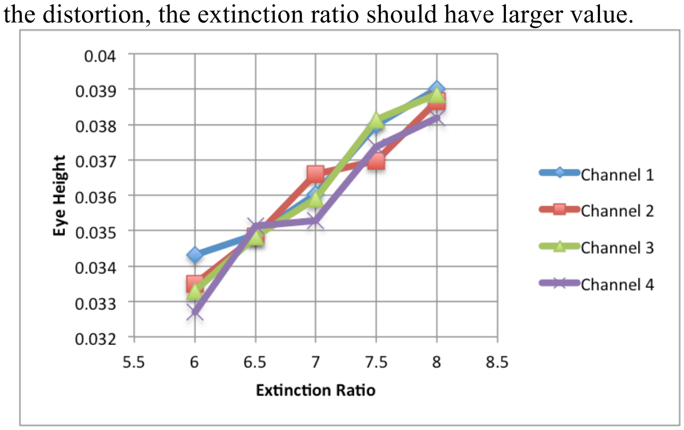



Fig11: Eye height vs. extinction ratio

As can be observed from figure 12, threshold decreased as the extinction ratio increased.

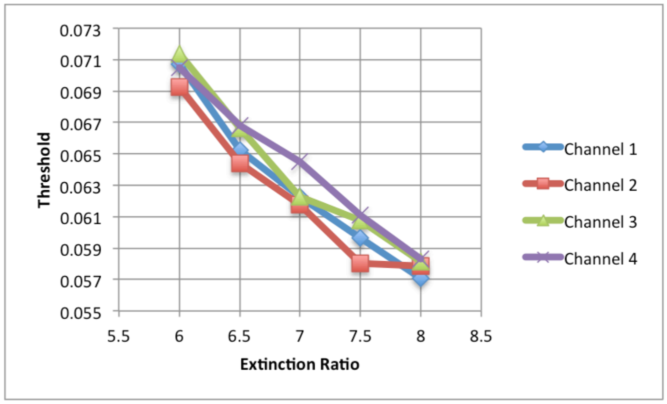



Fig12: Threshold vs. extinction ratio

## V. CONCLUSION

In this paper, 4 channels CWDM have been simulated. The powerful of CWDM comes from its large bandwidth with low cost. An EDFA has been used for long distances. As can be observed from the results, maximum Q factor, eye height, and threshold decreased as the fiber length increased. On the other hand, it does not appear that the extinction ratio has a specific pattern on maximum Q factor and minimum BER. However, as the value of extinction ratio increased, eye height increased but threshold decreased.

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## Appendix B: Conference Proceedings

# Performance Analysis of Bidirectional Broadband Passive Optical Network Using Erbium Doped Fiber Amplifier

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## ABSTRACT

The broadband passive optical network (BPON) has the ability to support high-speed data, voice, and video services to home and small businesses customers. In this work, the performance of bi-directional BPON is analyzed for both down and up streams traffic cases by the help of erbium doped fiber amplifier (EDFA). The importance of BPON is reduced cost. Because PBON uses a splitter the cost of the maintenance between the providers and the customers side is suitable. In the proposed research, BPON has been tested by the use of bit error rate (BER) analyzer. BER analyzer realizes maximum Q factor, minimum bit error rate, and eye height.

Keywords: PON, BPON, WDM, EDFA, BER.

## 1. INTRODUCTION

The process of transporting information from one place to another by the use of light as a carrier is called optical fiber communication. Because the fiber has very large attenuation than the coaxial cable, optical fiber was not popular in 1970's. However, the attenuation of the optical fiber is decreased to 0.2dB/km. Using fiber optics carries many advantages such as high communication capacity, reduced transmission loss, and immunity to electromagnetic interference [*1*]. The service providers that are called central offices (COs) are connected to businesses and residential subscribers by the access network. The requests of bandwidth on the access network has been growing exponentially over past many years [*1*]. Because of this excessive demand on bandwidth, fiber-to-the-home (FTTH) based broadband access network was produced. Between different FTTH implementations, passive optical network (PON) is the suitable one [*3*].

In a PON, All components between the central office and the customer properties are not active. That means no power is needed. Passive optical components are used in PON in order to direct the traffic signals within a range of wavelengths to the user side and return back to the central office [*10*]. PON is an optical fiber connection that can provide much more bandwidth with the comparison of the coaxial cable. PON has many advantages such as providing high bandwidth, low maintenance cost because of using passive components in the network, and offering a large coverage area [*1*]. PON contains optical line terminals (OLT), which can be found in the central office, remote node (RN) which involves couplers/splitters in order to multiplex and de-multiplex the down and up streams traffic, and numbers of optical network units (ONUs), which takes the down stream traffic from RN and give it the up stream traffic [*1*].

Ethernet PON (EPON), Broadband PON (BPON), and Gigabit PON (GPON) are three standards of passive optical network. EPON is one type of passive optical network that transports data traffic enclosed in Ethernet frames. One main drawback in using EPON is its high cost [*15*]. One of the main advantages in using GPON is that links to all essential services are supported. The first time division multiplexing (TDM) PON system improved by FSAN was named Broadband Passive Optical Network (BPON) [*16*]. It depends on Asynchronous Transfer Mode (ATM) and is frequently referred to Asynchronous Transfer Mode Passive Optical Network (APON). In 1998, ITU-TG.983 series recommendations published the first BPON standards [ITU09] [*1*]. BPON's architecture is flexible and can accommodate with different situations. The mainly two differences between BPON and GPON are the data rates and customer data encapsulation technique. OLT and ONU are two main parts of BPON's architecture.

## 2. PON ARCHITECTURE

Figure 1 shows simple architecture of a typical basic PON which links switching components in the central office with several service subscribers by optical fiber. Inside central office, digitized voice and data are combined and sent downstream to clients by optical fiber by the use of a 1490 nm wavelength [*10*]. From clients to central office, which is called upstream uses a 1310 nm wavelength. In order to send video services downstream, a 1550 nm is required. However, video services cannot be sent upstream. As can be seen from the figure 1, all the clients use a 1310 nm upstream wavelength. For this reason, timing is important in order to avoid interference. The process starts in the central office and it ends in the central office also because the system has downstream and upstream [*10*]. At the central office, one single-mode fiber strand goes to an optical power splitter. Optical power splitter splits the optical power into number of paths. Each path runs to specified client. If the splitter is designed in order to divide the optical power evenly, then the power will go to each client is the optical power entering to the splitter divided by the number of paths. Unequal division of the optical power of the splitter is available according to the application [*10*]. The splitter can be designed to give number of paths ranging from 2 to 64. However, in PON, the splitter can be designed to provide 8, 16, or 32 paths. From the optical splitter, singular single-mode fibers go to the clients' houses and other serving buildings [*10*].

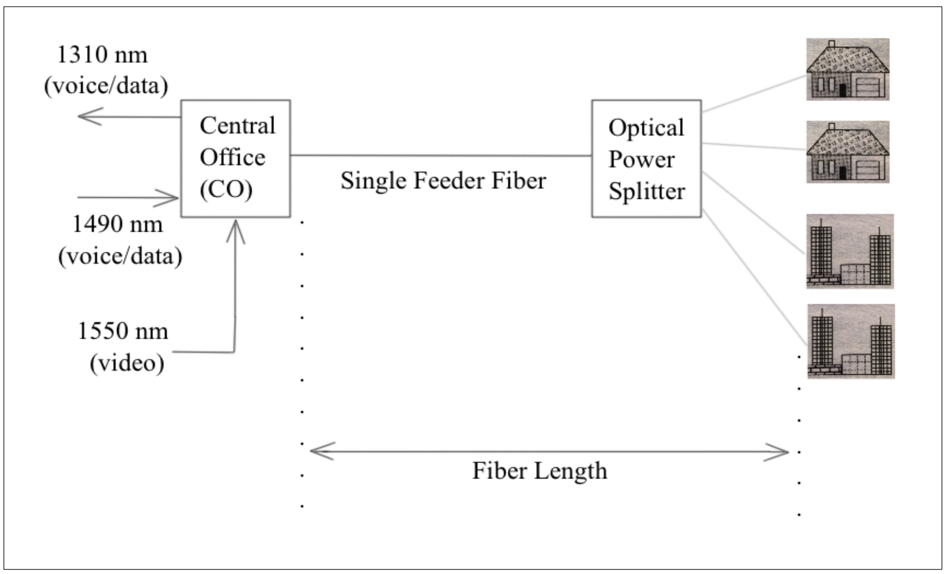



Figure 1: PON architecture

### 2.1. Optical Line Termination (OLT)

The optical line termination (OLT) is found in the central office. The objective of OLT is to control the bidirectional movement of information (data, voice, and video) across the network [*10*]. An OLT has to support the specific distance needed between the central office and the clients. In the downstream direction, an OLT has to take the information from the central office and distribute it to the clients. However, in the opposite direction, which is the upstream, an OLT has to accept and distribute various kinds of data and voice traffic from the network users [*10*]. A normal OLT is constructed to control more than one PON. Depend on the type of PON used in the system, downstream and upstream can operate at 155 Mb/s, 622 MB/s, 1.25 Mb/s, or 2.5 Mb/s. Also, depending on the application, the data rate of the downstream may be higher than the upstream. That means, it is not necessary that the data rate of the downstream and the upstream be equal [*10*].

### 2.2. Optical Network Unit (ONU)

An optical network unit (ONU) is located in an outdoor component shelter nearby the clients' properties. These shelters may contain shelters placed at a curb inside office park. Therefore, the ONU must accommodate with different temperature situations. Also, the ONU when it is located outdoor should have resistance to water and has the ability to stand high winds. Furthermore, it has to have local power supply and battery as a buck up. The connection between the ONU and the client's properties can be a coaxial cable, twisted-pair copper, optical fiber, or wireless connection.

## 3. SIMULATION

In order to analyze the performance of the downstream and upstream traffic, the simulation shown in figure 2 was used. Components such as CW laser, pseudo random bit sequence generator (PRBSG), non-return-to-zero (NRZ), return-to-zero (RZ), optical circulator, single optical fiber, EDFA, and BER analyzer have been used. The parameters of some components used in the simulation can be seen in table 1. In the ONUs shown in figure 2 transmitters to generate the upstream. Therefore, in the upstream case, the optical splitter will act as an optical combiner. These signals generated will travel through the single optical fiber to the central office in order to test the quality of the signals by BER analyzer.

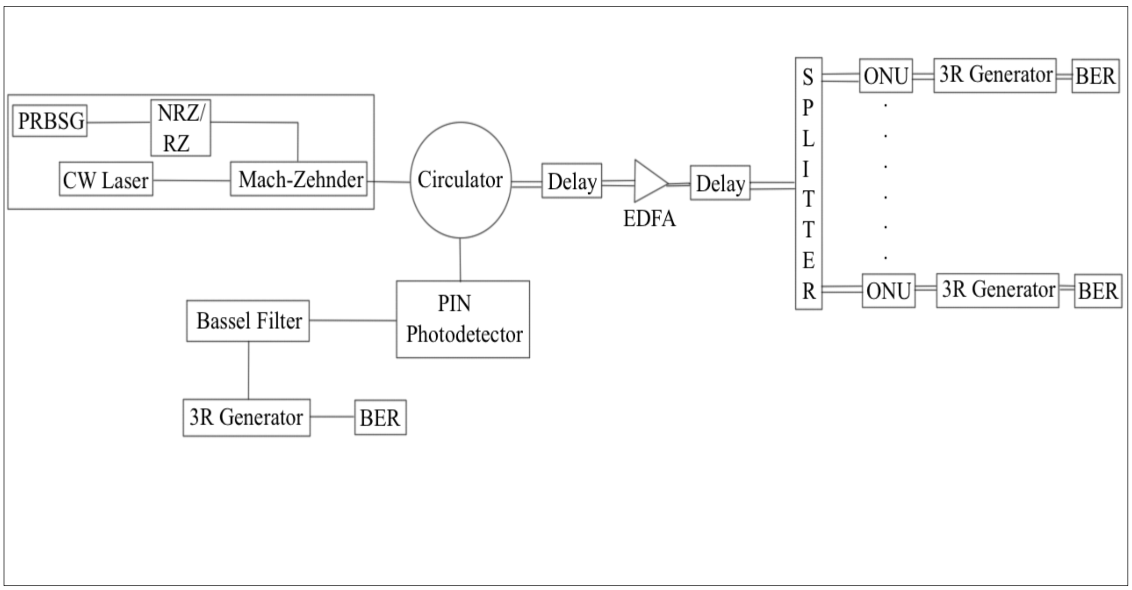



Figure 2: Simulation set up

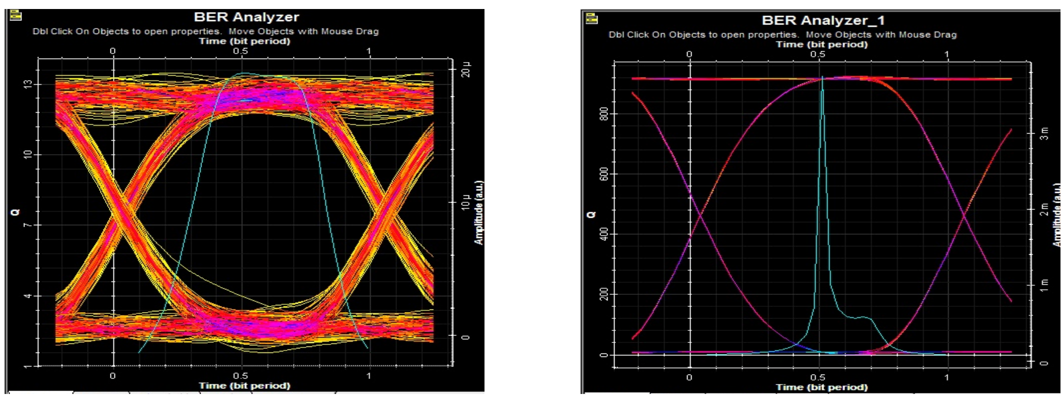
| Side | Component | Parameter | Value |
|---|---|---|---|
| Transmitter | NRZ Pulse Generator | Amplitude | 1 a.u. |
| | | Rise Time | 0.05 bit |
| | | Fall Time | 0.05 bit |
| | RZ Pulse Generator | Amplitude | 1 a.u. |
| | | Rise Time | 0.05 bit |
| | | Fall Time | 0.05 bit |
| | CW Laser | Frequency | 1550 and 1300 nm |
| | | Power | 0 dBm |
| | | Linewidth | 10 MHz |
| | Mach-Zehnder | Extinction Ratio | 15 dB |

| Channel | Single Optical Fiber | Length | 20, 40, 60, 80, 100, 120, 140, and 150 km |
|---|---|---|---|
| | | Attenuation | 0.25 dB/km |
| | Optical Splitter | Number of output ports | 8, 16, and 32 |
| Receiver | PIN Photodetector | Responsivity | 1 A/W |
| | | Dark Current | 10 nA |
| | Bessel Filter | Cutoff Frequency | 0.75*Bit rate Hz |

Table 1: Parameters of some components used in the simulation

## 4. RESULTS AND DISCUSSION

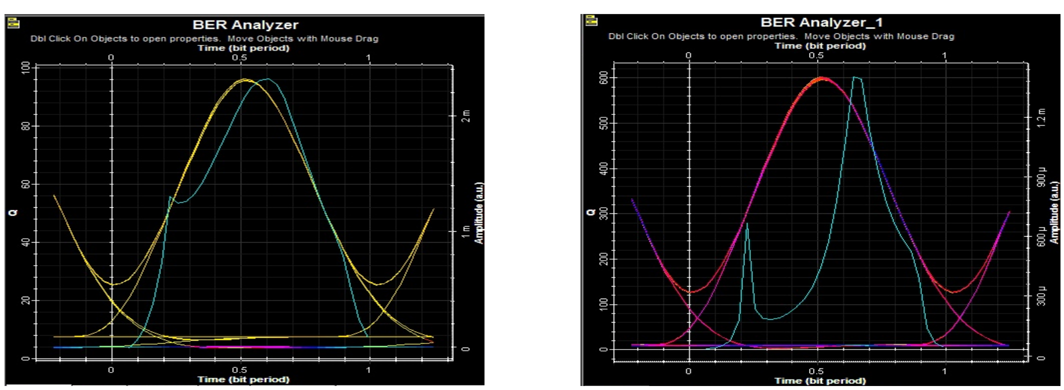
The results have been made according to the optical fiber length, coding technique, and number of users. Optical fiber length was chosen to vary from 20km to 150km. For coding technique, NRZ and RZ coding techniques were used. 8, 16, and 32 numbers of users have been tested in this paper. Eye diagrams were obtained in order to test the performance of the signals in either the downstream or upstream directions. Three parameters have been tested, which are maximum Q factor, minimum bit error rate, and eye height. These three parameters are essential in order to test the signal performance received in the optical communication system. In figure 3, eye diagrams for 8 users with 20km optical fiber length for both downstream and upstream are shown.



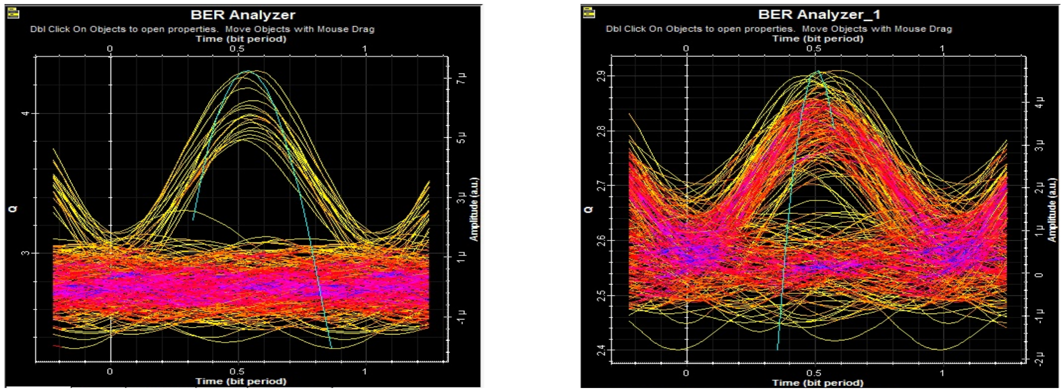

(a) (b)

Figure 3: Eye diagrams for 8 users with 20km fiber length using NRZ technique. (a) Upstream (b) Downstream

The eye diagrams of 32 users using RZ technique for both upstream and downstream traveling 20km and 150km distance are shown in figure 4. When the signal travels 20km, which is relatively short distance, the signal is very clear and undistorted. On the other hand, when the signal travels 150km, which is relatively long distance, the signal is very distorted and unclear.




(a) (b)

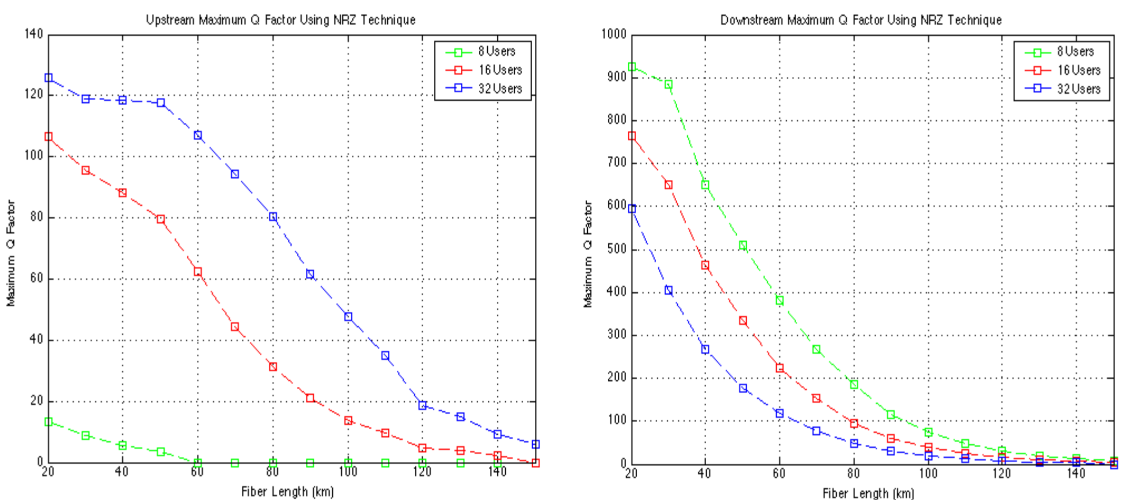



(c) (d)

Figure 4: 32 users using RZ technique. (a) Upstream 20km fiber length. (b) Downstream 20km fiber length. (c) Upstream 150km fiber length. (d) Downstream 150km fiber length.

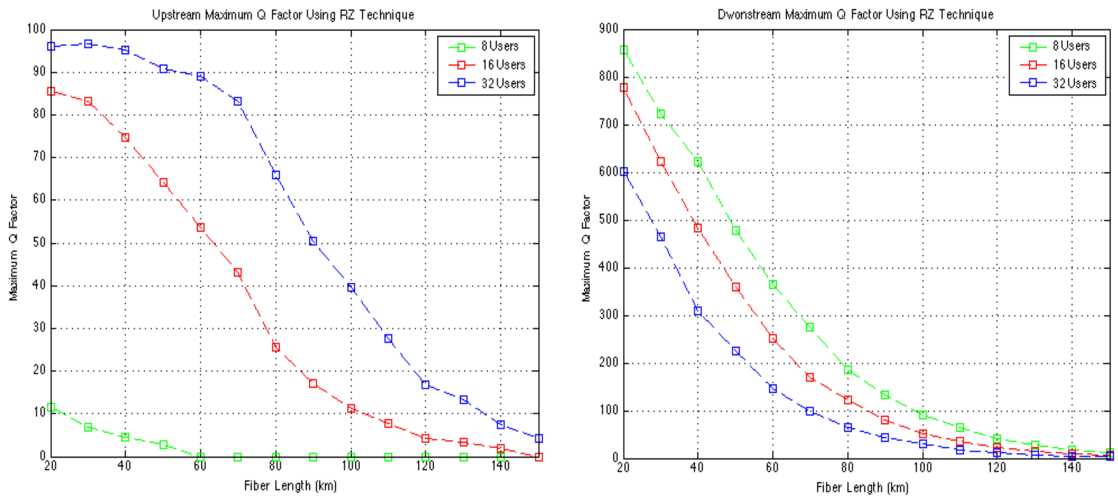
### 4.1. Maximum Q Factor

In this section, maximum Q factor has been tested. Maximum Q factor is a parameter that is proportional to signal-to-noise ratio (SNR) [*19*]. It is a dimensionless quantity that tests the quality of the signal. In figure 5 and 6, the maximum Q factor for both upstream and downstream is analyzed according to the fiber length, coding technique (weather it is NRZ or RZ), and number of users. As can be seen the Q factor is higher in the downstream direction when using NRZ or RZ. When NRZ was used, the Q factor for downstream direction exceeded 900. However, when RZ was used, Q factor was below 900. Similarly, for upstream, the Q factor when using NRZ exceeded 120, but when using RZ, the Q factor was below 100. That means, NRZ coding technique is better than RZ.




(a) (b)

Figure 5: Maximum Q Factor Using NRZ technique. (a) Upstream (b) Downstream

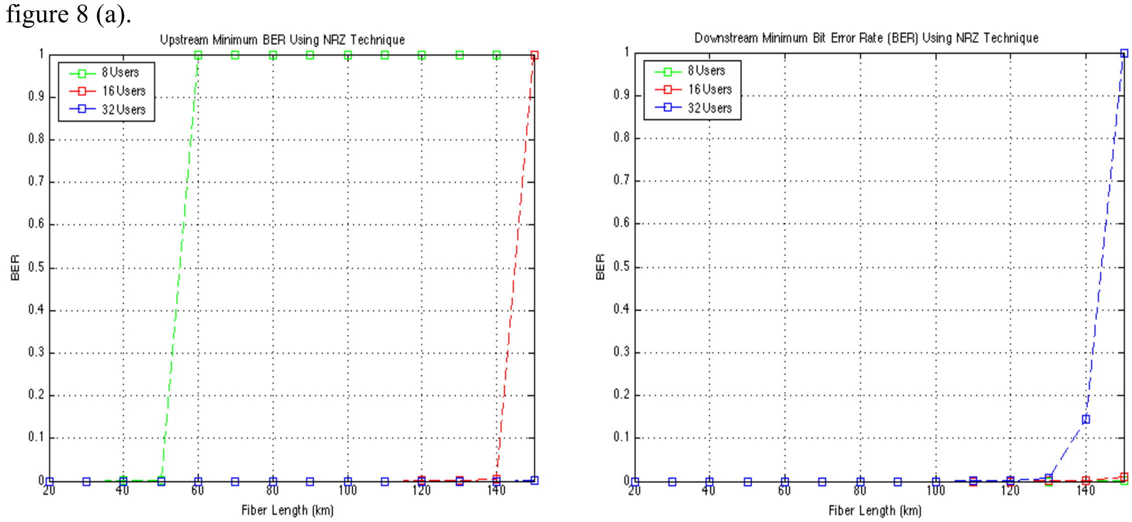



(a) (b)

Figure 6: Maximum Q Factor Using RZ technique. (a) Upstream (b) Downstream

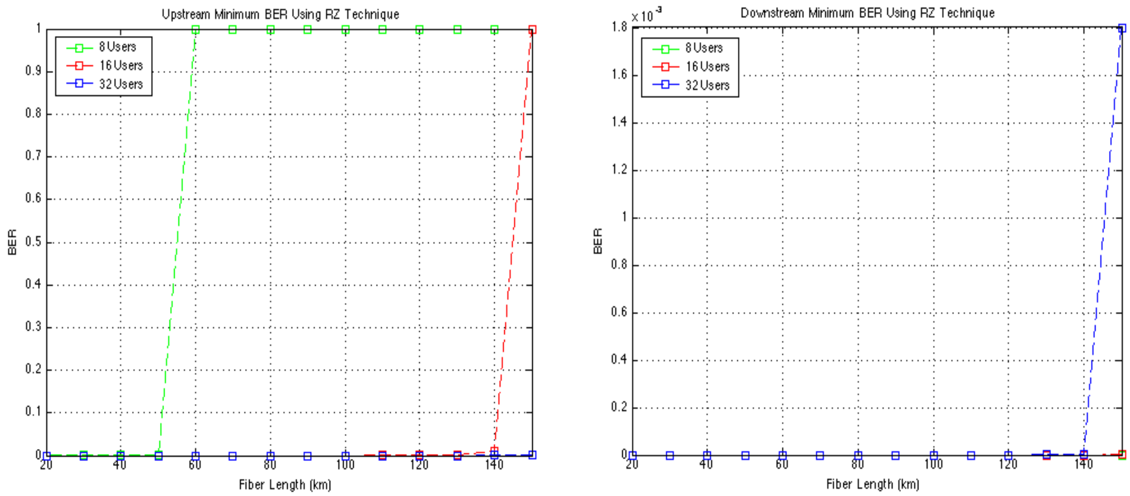
### 4.2. Minimum Bit Error Rate (BER)

Minimum bit error rate (BER) is also dimensionless parameter which is used to test the performance of the signal. It can be defined as the ratio of the number of bit errors discovered in the receiver side to the number of the bit addressed [*19*]. According to the definition, the result of the ratio should be zero or very small quantity in order to be the transmission process satisfied. If the result is 1, means that all the bits transmitted are with errors. As can be seen from figure 7 (a), the signal for 8 users was completely destroyed when it reached 60km fiber length. However, the BER was still around zero for 8 users downstream direction. The same case happened when RZ was used as a coding technique as can be seen in figure 8 (a).




(a) (b)

Figure 7: Minimum BER Using NRZ technique. (a) Upstream (b) Downstream

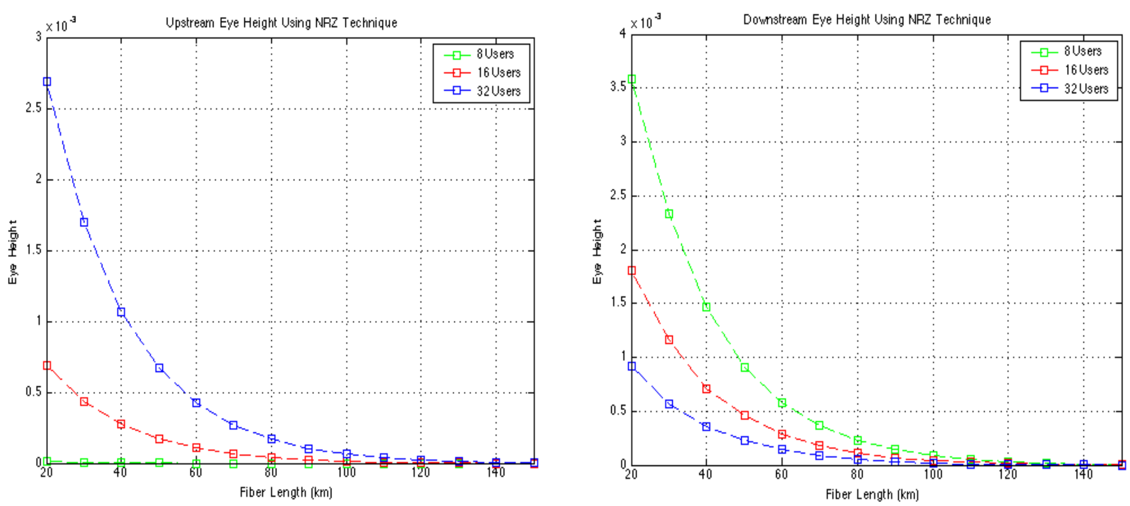



(a) (b)

Figure 8: Minimum BER Using RZ technique. (a) Upstream (b) Downstream

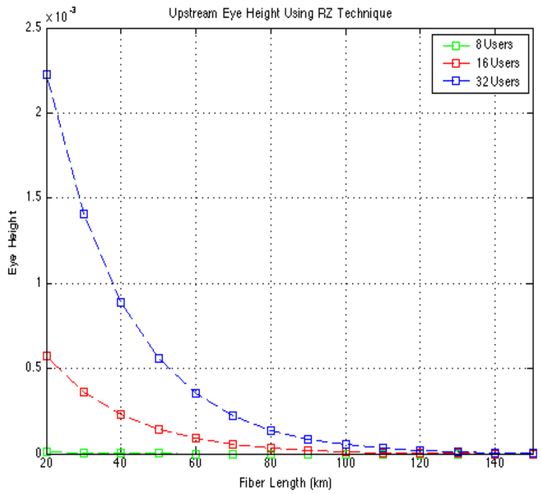
### 4.3. Eye Height

The height of the eye indicates the distortion happened to the signal. When the height of the eye is largest, less distortion happened to the signal [*10*]. As can be observed from the figures 9 and 10, the eye height is largest when RZ technique was used for 8 users in the downstream direction. Also, the lowest height of the eye happened when RZ was used for 32 users in the upstream direction. However, when NRZ was used in the upstream and downstream, eye height had close values for 8 and 32 users.

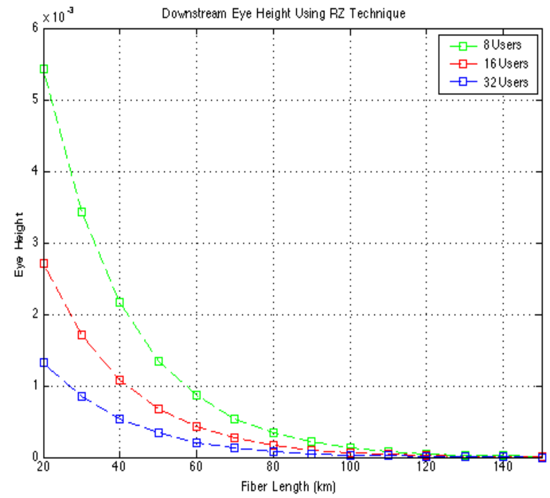



(a) (b)

Figure 9: Eye height Using NRZ technique. (a) Upstream (b) Downstream




(a)




(b)

Figure 10: Eye height Using RZ technique. (a) Upstream (b) Downstream

## 5. CONCLUSION

In this paper, bi-directional BPON access network using EDFA has been studied. The performance of the system has been studied according to three parameters, which are the length of the fiber, number of users, and coding techniques. From the results done, the BER increased as the length of the fiber and number of users increased. It has been observed that NRZ has better results than RZ coding technique.

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