FLEXIBLE OPTICAL FIBER ACCESS NETWORKS USING WAVELENGTH SELECTIVE SWITCHES

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โครงข่ายเข้าถึงเส้นใยแสงแบบยืดหยุ่นโดยใช้สวิตซ์แบบเลือกความยาวคลื่น

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การไขว้แทรกของการสวิตช์ทางแสงเป็นปัญหาสำคัญของระบบการสื่อสารด้วยแสงที่ทำให้เกิดการผิดเพี้ยนของสัญญาณและจำกัดประสิทธิภาพของระบบวิทยานิพนธ์เล่มนี้ศึกษาและนำเสนอแนวทางการออกแบบโครงข่ายไฟเบอร์ทูเดอะเอ็กซ์(fiber-to the x: FTTx)บนเทคโนโลยีการมัลติเพล็กซ์แบบแบ่งความยาวคลื่นของโครงข่ายเชิงแส งแบบพาสซีฟ (wavelength division multiplexing passive optical network: WDM-PON) ร่วมกับ สวิตช์ทางแสงของอุปกรณ์สวิตช์แบบเลือกความยาวคลื่นชนิดแอคทีฟ (wavelength selective switch: WSS) โดยโครงสร้างของระบบใช้จำนวนความยาวคลื่น 4 และใช้จำนวนยูนิตโครงข่ายแสง (optical network unit: ONU) เท่ากับ 10 สำหรับระบบการสื่อสัญญาณแสงด้วยอัตราบิต 10 กิกะบิตต่อวินาทีต่อความยาวคลื่น และ 40 กิกะบิตต่อวินาทีต่อความยาวคลื่น นอกจากนั้นตัวควบคุมการแจกจ่า ยความยาวคลื่นแบนด์วิธแบบพลวัต (dynamic wavelength bandwidth allocation: DWBA) ถูกใช้เพื่อควบคุมแอคทีฟสวิตช์ระบบความเร็ว 10 กิกะบิตต่อวินาทีใช้การมอดูเลตสัญญาณแบบออนออฟคีย์อิ้งชนิดไม่กลับสู่ศูนย์ (non-return to zero on-off keying: NRZ-OOK)และระบบความเร็ว40 กิกะบิตต่อวินาทีใช้การมอดูเลตสัญญาณแบบดิฟเฟอเรนเชียลดีคิวพีเอสเคชนิด ไม่กลับสู่ศูนย์ (non-return to zero differential quadrature phase-shift keying: NRZ-DQPSK) วิทยานิพนธ์นี้ศึกษาและวัดประสิทธิภาพของระบบที่ดีขึ้นโดยพิจารณาจากค่ากำลังรับของสัญญาณแสงที่ต่ำที่สุดและค่าอัตราผิดพลาดบิต (bit error rate: BER) ในการทำให้คุณภาพของสัญญาณดีขึ้น กระบวนวิธีลดการผิดเพี้ยนของสัญญาณทำได้โดยเพิ่มการหน่วงเวลาที่เหมาะสมของ WSS ทั้ง 3 ชนิดได้ถูกนำเสนอในวิทยานิพนธ์นี้การวิเคราะห์ทำโดยใช้คอมพิวเตอร์ซิมมูเลชั่ นด้วยซอฟท์แวร์ออพติซิสเต็มโดยไม่มีการทดลองจริง ระยะทางการสื่อสัญญาณสูงสุดเท่ากับ 20 กิโลเมตรโดยใช้เส้นใยแสงชนิดโหมดเดียว single mode fiber (SMF) ตามมาตรฐาน ITU-T G.652.D ที่ค่า BER เท่ากับ 10^{-4}. โดยไม่ใช้การแก้ไขความผิดพลาดแบบฟอร์เวิร์ด (forward error correction: FEC) ผลการศึกษาพบว่าค่ากำลังรับของสัญญาณแสงที่มีระดับ BER ที่ต้องการลดน้อยลงเมื่อเพิ่มการหน่วงเวลาให้กับค่าคุณลักษณะการสวิตช์ของ WSS ท้ายสุดค่าต้นทุนกำลังดีขึ้น 3 dB เมื่อใช้ค่าหน่วงเวลาเท่ากับ 3τ สำหรับสวิตช์ชนิดอิเล็คโตร-ออพติกสำหรับระบบทั้งสองแบบ.

สาขาวิชา วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต ....
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KEYWORD: Fiber to the x (FTTx), Flexible Fiber Access Network, Wavelength Selective Switch (WSS), Wavelength Division Multiplexing Passive Optical Network (WDM-PON), Optical Switching Characteristics, Switching Delay Time.

Maung Maung Htwe : FLEXIBLE OPTICAL FIBER ACCESS NETWORKS USING WAVELENGTH SELECTIVE SWITCHES. Advisor: Asst. Prof. Pasu Kaewplung, Ph.D.

The optical switching crosstalk is the important considerable issue in the optical fiber communication system, it tends to the signal distortion and decreasing of the system performance. This dissertation research is proposed a guideline to design a flexible fiber to the x (FTTx) system based on wavelength division multiplexing passive optical network (WDM-PON) combining with wavelength selective switches (WSSs). For the system configuration, the 4 wavelengths-10 ONUs system with the data bit rate of 10-Gbps/λ and 40-Gbps/ λ are studied in this dissertation. Moreover, to be active switching, the dynamic wavelength bandwidth allocation (DWBA) controller is used to control WSSs. The modulation format NRZ-OOK is applied for 10 Gbps/λ system and the advanced modulation format NRZ-DQPSK is applied for 40 Gbps/λ system. The investigation of this dissertation is mainly focus on the improvement of system performance such as the minimum received optical power and power budget related with bit error rate(BER). In order to improve the system performance, the signal distortion reduction methodology is applied by adding the proper delay times in switching characteristics of 3 different types of WSS. The results of investigation come from only the computer simulation by using the commercial OptiSystem software without performing real experiments. The maximum reach of data transmission is limited to 20 km over ITU-T G652.D SMF fiber with the limited BER=10^{-4} (without using forward error correction: FEC). As the results based on worst case BER, the received optical power for both system designs are improved after providing proper delay times in switching characteristics of WSS. Obviously, the power budget is improved by about 3 dB after providing 3τ delay time of electro-optic switch for both system designs.

Field of Study: Electrical Engineering | Student's Signature..............................

Academic Year: 2018 | Advisor's Signature.............................

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Maung Maung Htwe

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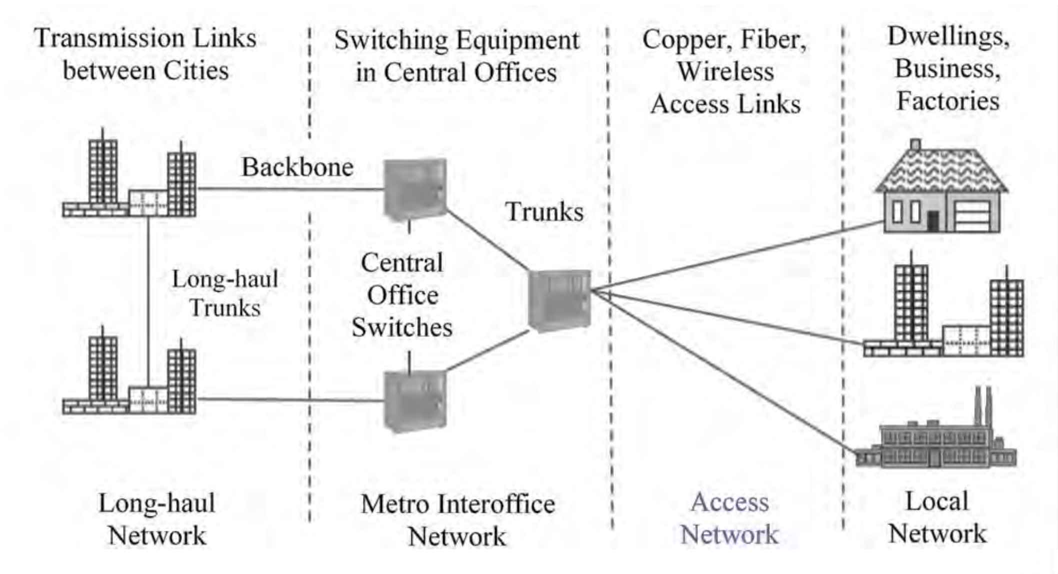
CHAPTER 1
INTRODUCTION

As we begin the new millennium age, we are seeing dramatic changes in the telecommunications industry that have far-reaching implications for our lifestyles. There are many factors for these changes. First and foremost is the continuing, relentless need for more capacity in the network. This demand is fueled by many factors. The tremendous growth of the Internet and the World Wide Web (commonly known as www.) that in terms of the number of users and the amount of time. Therefore, the bandwidth taken by each user is a major issue. For a high level networking, it can be categorized into a metropolitan network and a long haul network. The metropolitan network is the section of the network that exists in a large city or a region. The long-haul network provides the connection of the different cities or regions. The metro network is organized by a metro access network and a metro inter-office network [1].



a

Figure 1-1 Describing a public network structure [2]

The access network, finally, refers to the “last mile” from a node in the metro network out to the individual users of a telecom service. In order to distinguish the directions of traffic flow, the downstream refers to a transmission from the central office to users whereas the upstream is the transmission from the users to the central office [2]. The bandwidth requirements of users in the telecommunication network rapidly increased during the recent years. Nowadays, the ultra-high definition (8K) display has been emerged and become more popular. The emerging optical access network must supply the bandwidth demand for each user as well as support high data rate, broadband multiple services and flexible communications for various end-users.

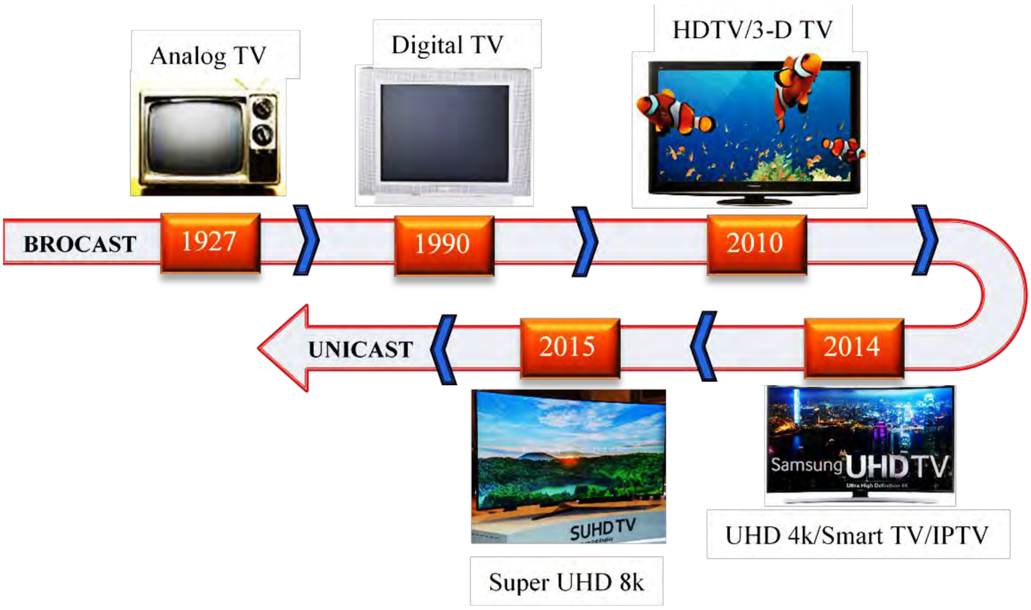


Figure 1-2 Evaluation of display [3]

Being considered as sophisticated and economical optical access networks for new broad-band services and emulation of legacy services, passive optical network (PON) provides as one of the solutions to be attractive access network [4]. The combining technique of time division multiplexing, wavelength division multiplexing and [5] PON system is used for the high resource efficiency and capacity network in which namely as TDM-PON and WDM-PON, respectively. Although TDM-PON provides much higher bandwidth for data application, it has limited end-users availability issue. However, WDM-PON is the attractive problem solving that face in TDM-PON by allocating a specified wavelength to each user. Moreover, it can also provide with point to point (P2P) and high data rate transmission channel between the central office (CO) and each subscriber.

The application of PON technology is to provide the broadband connectivity in the access network to multiple-occupancy units, homes and small businesses namely as fiber to-the-x (FTTx). This application is used in the FTTx designation. Where *x* stands for premises, curb, home, building, desktop or something else and it was indicating that how about the fiber endpoint closely comes to the actual user. The following are the acronyms used in the commercial and technical literature;

1) Fiber-to-the-business (FTTB): it refers to the deployment of optical fiber from a central office that switched directly to an enterprise.
2) Fiber-to-the-curb (FTTC): it describes installing optical fiber cables from the equipment of central office to a communication switch that located within 1000 ft of enterprise or a home. The twisted pair copper wires, coaxial cables that used for DSL or some other transmission channels are used to connect the equipment of curbside and the customers in a building.
3) Fiber-to-the-home (FTTH): it stands to the providing of optical fiber from a central office that switched directly into a home. Typically, the difference between FTTB and FTTH is that larger bandwidths demand in businesses over a greater sector of the day than home users do. As a result, a network service provider can collect more installation cost effectiveness from FTTB networks than for FTTH networks.
4) Fiber-to-the-neighborhood (FTTN): it might refer to a PON structure in which optical fiber cables install within 3000 ft of businesses, homes and being provided by the network.
5) Fiber-to-the-office (FTTO): it is the similar function of FTTB because an optical transmission is provided by all the ways to the premises of a business customer.
6) Fiber-to-the-premises (FTTP): it has the various FTTx concepts to become the prevailing term of encompasses. Therefore, FTTP architectures contain the implementations of FTTB and FTTH networks. FTTP network also can be used in BPON, EPON, or GPON technologies.
7) Fiber-to-the-user (FTTU): it is the similar way to the applications of FTTB and FTTH networks [2].

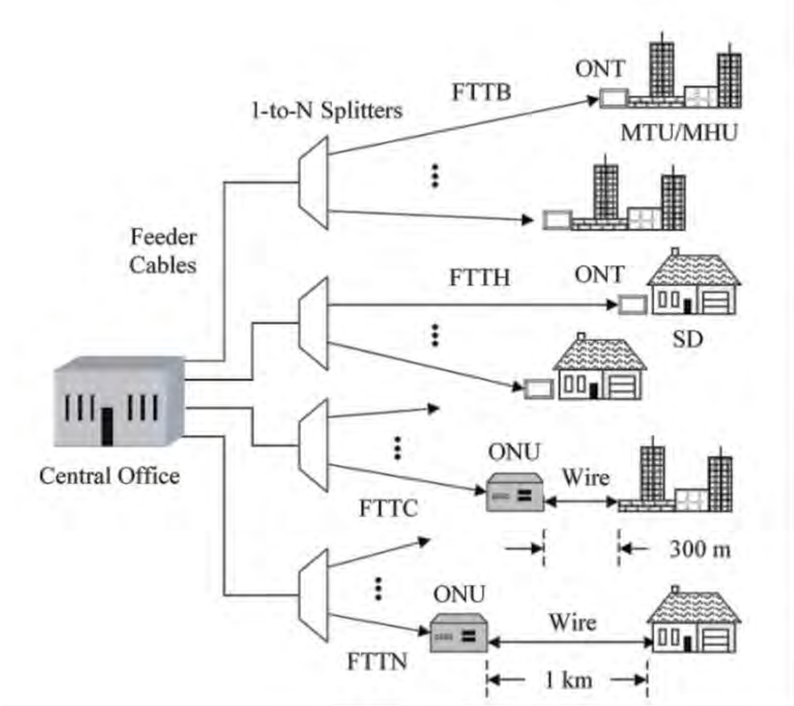


Figure 1-3 Some FTTx scenarios [6]

PON technology has no active elements in the field and, thus, power and heat issues can be eliminated and the coarse wavelength division multiplexing passive optical network (CWDM-PON) could be deployed in FTTx environment where a high bandwidth requirement is one of the major demanding factors from the subscribers [6]. Most of FTTx systems are so-called "triple play" systems offering voice (telephone), video (TV) and data (Internet access). To provide all three services over one fiber, signals are sent bi-directionally over a single fiber using several wavelengths of light. Nowadays, the FTTx based on PON technology is the key solution of bandwidth hunger and can support the data rate of 10 Gbps based on 10GE-PON (IEEE 802.3av) [7] and ITU-T G987 XG-PON standards [8].

In recent, NG-PON2 (ITU-T) standard [9] can provide the downstream and upstream data rate of 40 Gbps and 10 Gbps respectively. Currently, to approach the flexibility of FTTx, the wavelength selective switch (WSS) has undertaken development to assign the reconfigurable optical add/drop multiplications in multiwavelength optical network. As a result, WSS become the most widely used device and also popular among the flexible solutions for flexible networks in the near future [10]. Focusing on the FTTx system based on fiber access network, it can be improved the efficiency of bandwidth utilization by accommodating different data rate into one port of optical line terminal (OLT), and ensuring the flexible allocation of bandwidth to meet the different demands of subscribers [11]. The research about the performance limitation of 10 Gbps per channel based 16 channels CWDM-PON by using arrayed waveguide gratings (AWGs) as a multiplexer at optical line terminal (OLT) side and a passive wavelength splitter at optical network unit (ONU) [12] has been successfully conducted. Moreover, the high data bit rate transmission with 40 Gbps with advanced modulation formats over PON research also have been studied [13], [14]. The study of efficient and flexible PON network employing dynamic wavelength allocation (DWA) and using AWGs as a multiplexer at OLT side also has been demonstrated [15]. Recently, optical networks employing wavelength routing devices have gained considerable attention [16] [17].

1.1 Aim and Objectives

The main goal of this dissertation research is to be a guideline for designing a flexible FTTx system based on WDM-PON technology combining with the active WSSs and considering on the switching characteristics of WSS.

The objectives can be categorized as follows:

1) To propose 4 wavelengths-10 ONUs fiber access network design with the data rates of 10 Gbps/ λ and 40 Gbps/λ.
2) To investigate and reduce the signal distortion due to the optical switching crosstalk of WSS by adding the proper delay times in the switching characteristics of 3 different types of WSS.
3) To improve the system performance as the minimum received optical power and power budget related with the worst case of BER=10^{-4} (without forward error correction:FEC).

1.2 Scope and Limitations

The scope and limitations of this dissertation research are shown as the following:

1) Designing FTTx system using active WSSs incorporated with DWBA and simulate the system by using the OptiSystem software without performing real experiments.

2) Using only the SMF ITU-T G.652.D as a transmission fiber for both data rates of 10 Gbps/λ and 40 Gbps/λ.
3) Limiting the maximum reach of the system by 20 km for both data rates.
4) Providing the following active WSSs in investigation.
    - Photonic crystal switch with $\tau = 0.5$ ps.
    - GaInAs/InP multiple quantum well switch (MQW) with $\tau = 100$ ps.
    - Electro-optic switch with $\tau = 5$ ns.
5) Ignoring the impact of polarization mode dispersion and fiber nonlinearity because of short distance access network.
6) Setting with the number of channel is limited by 4(4 CWDM wavelengths: 1471-1531 nm) to 10 ONUs for both data rates.

1.3 Outlines of the Thesis

The rest of this thesis are organized as follows: the details of design technology and components of a lightwave system are discussed in CHAPTER 2. And then, proposed system designs and methodology are expressed in CHAPTER 3. Results are presented in CHAPTER 4 and finally, discussion and conclusion of this dissertation work are drawn in CHAPTER 5.

CHAPTER 2
TECHNOLOGY AND COMPONENTS OF A LIGHTWAVE SYSTEM

In order to approach the designing of proposed system, the design technology and basic theories of system components are the key issue to be a complete structure. Therefore, the technology and basic theories of system are discussed in this chapter.

2.1 Passive Optical Network (PON)

For the network and service providers, attempting to reduce their operational costs, an attractive strategy is using the concept of a passive optical network(PON). As a PON structure, there are no active elements between the central office and the customer's premises. Moreover, it used only passive optical components that are setup in the network transmission path to manage the traffic signals included in the specific optical wavelengths to the user subscribers and send back to the CO. By replacing the active components with passive components, it can provide with cost saving scenario to the service provider by omitting power requirement and manage active devices in the cabling of the access network system [2].

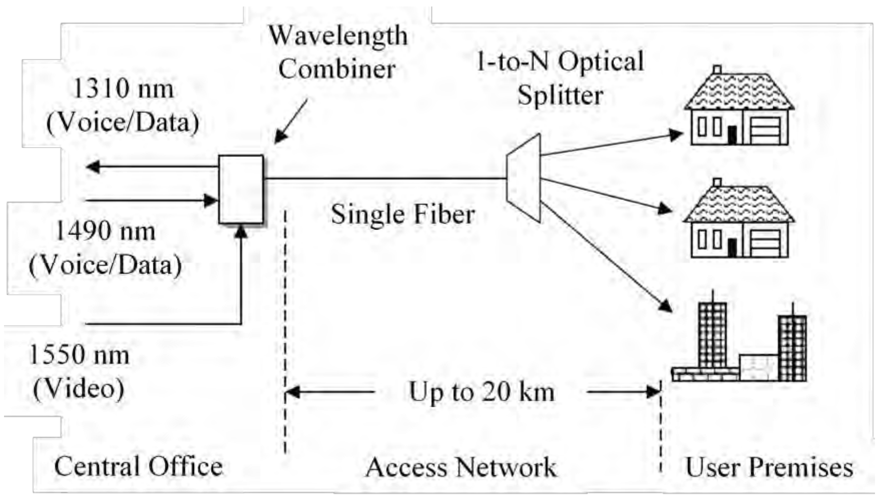


Figure 2-1 A typical passive optical network structure [2]

The system architecture of PON is consisted of an optical line terminal (OLT), an optical fiber with a passive power splitter and an optical network unit (ONU) or optical network terminal (ONT), respectively. An OLT is located at a central office of the internet service provider where it is an inter-connection to the backbone network. Then, signals sent from OLT will be fed into a fiber to the destination area. A passive splitter located at the remote node or distribution point will split optical signal into many branches. Each split signal is then arrived the ONU, located at a house or building, and convert optical signal into electrical signal with a proper interface to the user's equipment [18].

The length of optical fiber transmission from the central office to the user might be up to 20 km. Therefore, the active components contain only in the central office and at the subscriber. There are many alternative PON implementation scenarios. The three main structures are broadband PON (BPON), Ethernet PON (EPON) and gigabit PON (GPON) [2]. The 10 Gbps-ethernet passive optical network standard also well known as 10G-EPON supports network connections over telecommunication provider infrastructure. The standard supports two configurations: symmetric, operating at 10 Gbit/s data rate in both directions, and asymmetric, operating at 10 Gbit/s in the downstream (provider to user) direction and 1 Gbit/s in the upstream (user to provider) direction. It was assigned as IEEE 802.3av standard in 2009. PON belongs to access networks. Access equipment is usually deployed in large volumes. They are therefore very cost-sensitive. In a PON system, the cost of ONU needs to be multiplied by the number of users. This cost is either borne by the service provider or the end user. Therefore, low cost is the most important consideration in ONU designs [19].

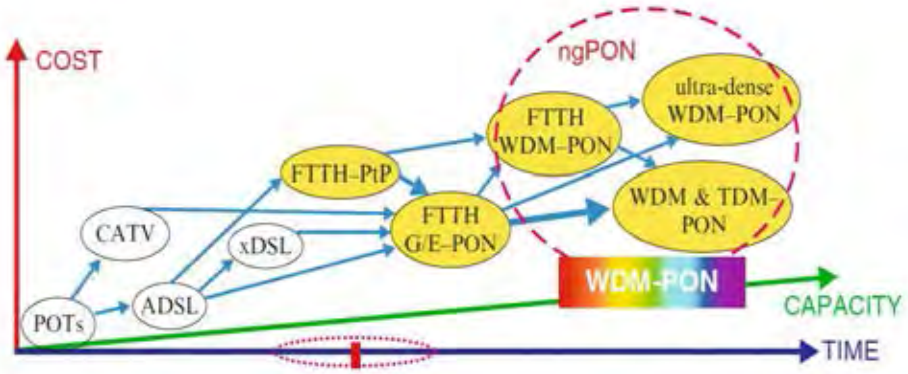


Figure 2-2 Evaluation of access network technologies [20]

Table 2.1 PON standards [18]

	BPON	GPON	EPON	10GEPON	XGPON
Standard	ITU G.983	ITU G.984	IEEE 802.3ah	IEEE 802.3av	ITU-T G.987
Downstream speeds	155Mbps, 622Mbps, 1.2Gbps	1.24Gbps, 2.5Gbps	1.25Gbps	10Gbps	10Gbps
Upstream speeds	155Mbps or 622Mbps	155Mbps, 622Mbps, 1.2Gbps, 2.5Gbps	1.25Gbps	10Gbps	2.5Gbps
Downstream wavelength	1480~1500nm	1480~1500nm	1500nm	1575-1580 nm	1575-1580 nm
Upstream wavelength	1260~1360nm	1260-1360nm	1310nm	1260-1280 nm	1260-1280 nm
Layer 2 support	ATM	Ethernet over GEM and/or ATM	Ethernet	Ethernet	Ethernet over GEM
Maximum PON splits	32	64	16	32	64
Distance	<20km	60km (max)	<20km	<20km	20km

2.2 Multiplexing Scheme

As multiplexing scheme, it can be used as independent dimensions in optical communication system as follows;

1) Time domain: Optical and Electrical Time Division Multiplexing (OTDM, ETDM), where each user optical network unit (ONU) has access to individually assigned time slots. This can be either static or dynamical as in optical packet switching (OPS), providing dynamic bandwidth allocation (DBA) for varying capacity demands.
2) Electrical frequency (FDM) domain, also known as subcarrier multiplexing (SCM), for Radio-over-Fibre (RoF), xDSL (Digital Subscriber Line) or others: Each Optical Network Terminal (ONT) has an assigned frequency; all channels are combined at the remote node and demultiplexed at the Optical Line

Terminal (OLT). With a similar multiplexing level like TDM, FDM suffers from Signal-to-Noise Ratio (SNR) and non-linearity limitations.

3) Wavelength (optical frequency) domain: Wavelength Division Multiplexing (WDM), with the possible different densities (Coarse-WDM CWDM, Dense-WDM DWDM) and static or dynamic wavelength assignment, offer the highest possibilities. In an access scenario, multiplexing levels between 20 and 100 wavelengths per fibre can be foreseen.
4) State of optical polarization (SOP) domain: This is limited to two orthogonal components; thus, its utilization is per se not attractive in access.
5) A special case is code division multiplexing (CDM), as it is not an independent physical domain, i.e. it exploits correlation techniques to open a mathematical multiplexing domain. It can be regarded as an asynchronous way of sharing the time or the frequency depending on the approach (e.g. coherence multiplexing, spread-spectrum), in the electrical or in the optical domain. These systems suffer from SNR limitations and technological complexity that limit the number of users to a fraction of the theoretically possible.

2.3 TDM-PON Vs WDM-PON

A TDM-PON uses a passive power splitter as the remote terminal. The same signal from the OLT is broadcast to different ONUs by the power splitter. Signals for different ONUs are multiplexed in the time domain. ONUs recognize their own data through the address labels embedded in the signal. Most of the commercial PONs (including BPON, G-PON, and EPON) fall into this category.

A WDM-PON uses a passive WDM coupler as the remote terminal. Signals for different ONUs are carried on different wavelengths and routed by the WDM coupler to the proper ONU. Since each ONU only receives its own wavelength, WDM-PON has better privacy and better scalability. However, WDM devices are significantly more expensive, which makes WDM-PONs economically less attractive at this moment [16].

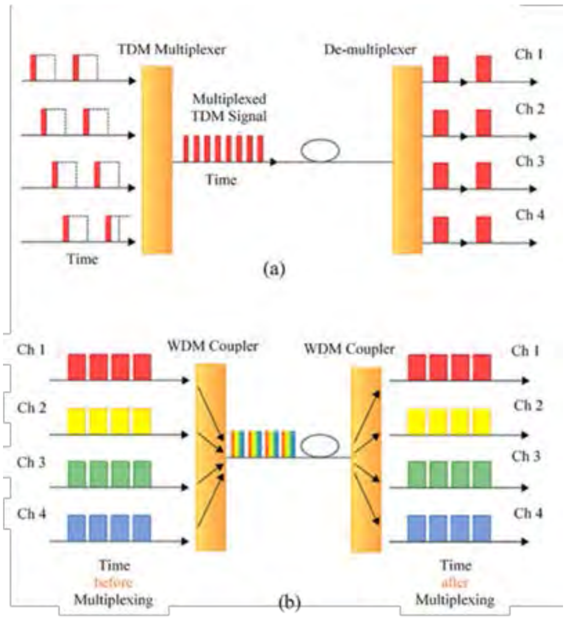


Figure 2-3 (a) Time Division Multiplexing; (b) Wavelength Division Multiplexing

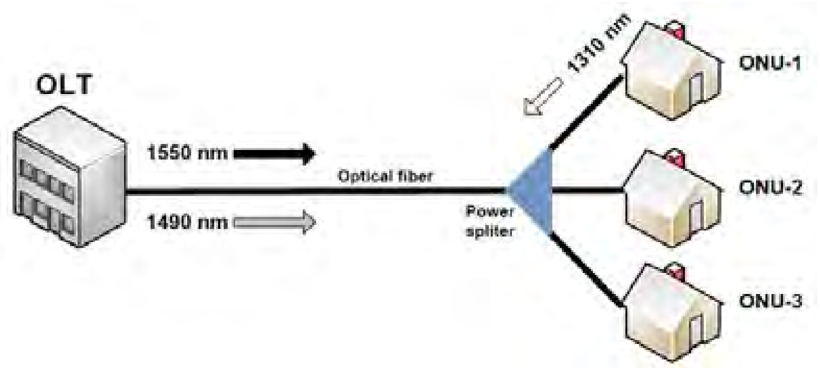


Figure 2-4 TDM-PON architecture [21]

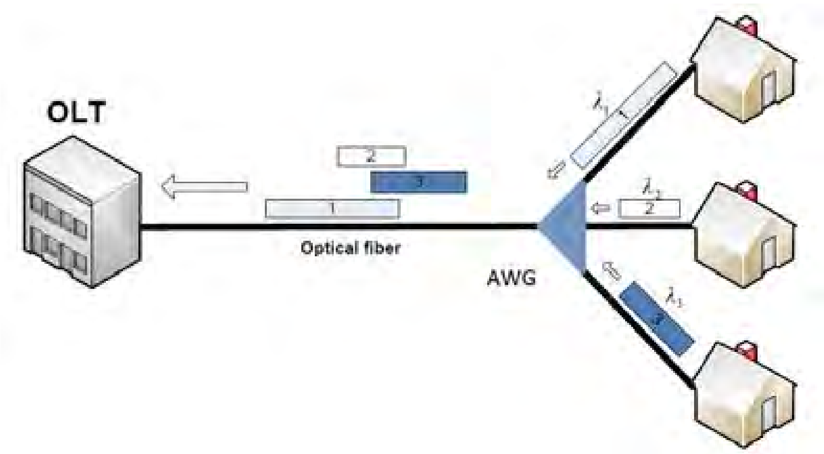


Figure 2-5 WDM-PON architecture [21]

Most PON systems deployed to date have been time division-multiplexed (TDM) systems. TDM-PON systems allow operators to take advantage of statistical multiplexing gains and make efficient use of last-mile bandwidth, and have enjoyed significant commercial success. But, scaling the speed of TDM-PONs by 10 times also will require 10 times the power budget, and 10-Gb/s TDM-PONs have required forward error correction to overcome that challenge. Chromatic dispersion effects also become significant at speeds above 10 Gb/s. Another challenge for TDM-PON is in the uplink direction, as multiple end-user ONTs all transmit to a single OLT at the central office. Thus TDM-PONs must support high-speed, burst-mode operation, with the end-user ONT only transmitting during an assigned time slot and the OLT receiver at the central office quickly synchronizing its clock and nimbly adjusting to accept the upstream packet burst. Such high-speed burst-mode OLT receivers are challenging to implement.

From a transmission perspective, WDM-PONs are much more scalable than TDM-PONs, because each end-user ONT can operate at its own speed (rather than, as with TDM-PON, requiring each end-user ONT to operate at the speed of the entire network). One of the main issues being the cost of components. To make efficient use of the optical spectrum inside fibers, WDM-PONs require dense WDM (DWDM), and DWDM lasers need thermoelectric cooler (TEC) controllers to maintain wavelength stability.

Coarse Wavelength Division Multiplexing (CWDM) is the technology of choice for cost efficiently transporting large amount of data traffic in telecoms or enterprise networks. CWDM typically has the capability to transport up to 16 channels (wavelengths) in the spectrum grid from 1270 nm to 1610 nm with a 20 nm channel spacing. Each channel can operate at either 2.5, 4 or 10 Gbps. CWDM cannot be amplified as most of the channels are outside the operating window of the Erbium Doped Fiber Amplifier (EDFA) used in Dense Wavelength Division Multiplexing (DWDM) systems. This results in a shorter overall system reach of approximately 100 kilometers. However, due to the broader channel spacing in CWDM, cheaper un-cooled lasers are used, giving a cost advantage over DWDM systems [22].

The wavelength channel assignments can be categorized as different schemes:

1) Static allocation
2) Semi-static allocation
3) Dynamic allocation

As statically assigning wavelength channels for end users is comparable to hard-wiring the infrastructure and that is functionally similar to the situation of recent networks. In a semi-static allocation, the wavelength selected functions at the end user network are not fixed. Otherwise, it can be changed on a non-frequent basis and the re-arrangement of the wavelength allocation can happen on a circuit switched basis.

The semi-static wavelength steering may also be used for provisioning capacity in response to slowly changing traffic patterns. When the wavelength selection mechanisms can operate fast, they may be able to operate on a per flow basis.

This dynamic allocation enables capacity-on-demand and directs the network resources (the wavelength channels) to those places in the network where the instantaneous traffic load requires them. Obviously, this also requires careful traffic monitoring and control processes on a 'per flow' level and thus a more complicated network management and control system [20].

2.4 Dynamic Bandwidth Allocation (DBA)

In early the previous version of PON implementations the bandwidth allocated to a specific user was guaranteed at a fixed value. This method results in a large amount of bandwidth remaining unused, since subscribers often have no information to send in their allocated time slots. A more efficient method is to allocate bandwidth to each user dynamically, depending on their specific needs at any given moment.

Dynamic bandwidth allocation (DBA) is a methodology that allows quick reapportioning of bandwidth on the PON based on current traffic requirements. The DBA process is controlled by the OLT, which issues grants or permits that allow an ONT to transmit within a specific time slot.

2.5 Components of a Lightwave System

The main components of fiber communications link are shown as follows:

1) Optical Fiber: The optical fiber is one of the most important devices in an optical link. A variety of fiber types exist, and there are many different cable configurations, depending on whether the cable is to be installed inside a building, in underground pipes, outside on poles, or under water.
2) Optical Transmitter: The transmitter consists of a light source and associated electronic circuitry. The source can be a light-emitting diode (LED) or a laser diode. The transmitter electronics are used to set the source operating point and to vary the optical output in proportion to an electrically formatted information input signal.
3) Optical Receiver: Inside the receiver is a photodiode that detects the weakened and distorted optical signal emerging from the end of an optical fiber and converts it to an electrical signal. The receiver also contains electronic amplification devices and circuitry to restore signal fidelity.
4) Passive Devices: Passive devices are optical components that require no electronic control for their operation. Among these are optical filters that select only a narrow spectrum of desired light, optical splitters that divide the power in an optical signal into a number of different branches, optical multiplexers that combine signals from two or more distinct wavelengths onto the same fiber (or that separate the wavelengths at the receiving end), and couplers used to tap off a certain percentage of light, usually for performance monitoring purposes.
5) Optical Amplifiers: After an optical signal has traveled a certain distance along a fiber, it becomes greatly weakened due to power loss along the fiber. At that point, the optical signal needs to get a power boost. This is done in long-distance links by means of an optical amplifier that boosts the power level completely in the optical domain. In a PON an optical amplifier is not employed in the outside cable plant but is used in a central office to boost the level of analog video signals before inserting them onto a fiber line.
6) Active Components: For a wide range of other active optical components, the electronic control for their operation will be required. These components include light signal modulators, tunable (wavelength-selectable) optical filters, variable optical attenuators, and optical switches. Since they are not used in a PON.

7) Connectors and Splices: Very low-loss optical connectors and splices are needed in a PON for joining cables and for attaching one bare fiber to another [2].

2.6 Optical Transmitter Section

The function of optical transmitters is to change form an electrical signal into an optical signal and to transmit the resulting optical signal via the optical fiber as a communication channel. It consists of an optical transmission source, a modulator and electronic circuits used to power and operate the two devices. The semiconductor laser and light emitting diode(LED) are used as the optical transmitting sources because of compact nature and compatibilities with optical fibers. The emitting of light is in the form of a continuous wave at a fixed wavelength (λ_0). The relation between carrier frequency(v_0) and this wavelength is $v_0 = c/\lambda_0$, where c is the speed of light in vacuum. In a recent lightwave systems, v_0 is counted from a set of frequencies standardized by the International Telecommunication Union (ITU). The spectral region near 1550 nm is commonly divided by the two bands namely the conventional(C band) and the long-wavelength (L band) [23]. The average optical power launched into the optical fiber is an important design parameter. Obviously, it should be as large as possible to improve the signal to noise ratio (SNR) of the receiver end. The transmitted optical power is rather low (less than -10 dBm) for light emitting diode whereas semiconductor laser transmitted power levels is exceeding 5 dBm. Although LEDs are very useful for some low data rate applications related to local-area networking. For computer-data transfer applications, most of light-wave systems provide semiconductor lasers as the optical transmitting sources. The bit rate of optical transmitters is limited by electronically rather than by the semiconductor laser. For the high speed design plan in recent, the optical transmitters can be operated at a high data rate of up to 40 Gbps [24].

2.7 Optical Receiver Section

The function of an optical receiver is to convert the received optical signal at the output end of the fiber link into the original source as electrical signal. Semiconductor photodiodes are used as photo detection because of the compact size and relatively high quantum efficiency. In a practice view, a *p-i-n* or an avalanche photodiode produces electric current that varies with time in response to the incident optical signal. It also adds some variables on noise to the signal, thereby reducing the SNR of the electrical signal. The accuracy of the decision circuit will depend on the electrical signal SNR level that generated at the photo-detector. It is important to design the receiver such that its noise level is not too high. The performance of a digital light-wave system is configured through the bit error rate (BER). Although the BER can be defined as the number of errors occurred per second so that the BER is depending on bit-rate. It is traditional to define BER, the average possibility of identifying a bit incorrectly. Depending on the system design, it is sometimes not possible to realize such low error rates at the receiver. The error correcting code is used to improve the raw BER of a light-wave system.

2.7.1 Noises

The shot noise and thermal noise are the two fundamental noise scenarios responsible with current fluctuations in all the optical receivers even if the incident optical-power P_{in} will be constant [25].

2.7.1.1 The Shot Noise

The shot noise means an action of the point that the electric current contains of a stream of electrons that are generated by random times. The noise variance is obtained by the equation;

$$\sigma_s{}^2 = 2qI_p\Delta f \tag{2-1}$$

Where, q = the charge of an electron (1.6021808×10^{-19} C)

$I_p = RP_{in}$, the average current of photodetector (A)

R = responsivity of the photodetector (A/W)

Δf = the effective noise bandwidth of the receiver (Hz)

When the dark current I_d is also generated by shot noise, the total shot noise is then given by;

$$\sigma_s{}^2 = 2q(I_p + I_d)\Delta f \qquad (2\text{-}2)$$

The quantity σ_s stands the root-mean-square (r.m.s) value of the noise current induced by shot noise.

2.7.1.2 The Thermal Noise

In a condition of a finite temperature, electrons can move randomly in any electric conductor. This thermal motion of electrons in a resistor behaves as a current fluctuation even without applying voltage. The load resistor at the front end of optical receiver combines this current fluctuations to the current generated by the photo-diode. This additional noise is referred to as thermal noise. It is also named Johnson noise or Nyquist noise. The variance of noise is obtained by the following equation;

$$\sigma_T{}^2 = (\frac{4k_B T}{R_L})\Delta f \qquad (2\text{-}3)$$

Where, k_B=1.38065 × 10^{-23} J/K (Boltzmann constant)

T= the absolute temperature (K)

R_L= the load resistor (Ω)

The same bandwidth appears in the case of both shot and thermal noises. Therefore, $\sigma_T{}^2$ is independent on the average current I_p, whereas $\sigma_s{}^2$ does. Therefore, the total current noise can be achieved by adding the benefits of shot noise and thermal noise;

$$\sigma_s{}^2 + \sigma_T{}^2 = 2q(I_p + I_d)\Delta f + (\frac{4k_B T}{R_L})\Delta f \qquad (2\text{-}4)$$

Table 2.2 Characteristics of common p-i-n photodiodes [25]

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength	λ	μm	0.4–1.1	0.8–1.8	1.0–1.7
Responsivity	R	A/W	0.4–0.6	0.5–0.7	0.6–0.9
Quantum efficiency	η	%	75–90	50–55	60–70
Dark current	I_d	nA	1–10	50–500	1–20
Rise time	T_r	ns	0.5–1	0.1–0.5	0.02–0.5
Bandwidth	Δf	GHz	0.3–0.6	0.5–3	1–10
Bias voltage	V_b	V	50–100	6–10	5–6

2.7.2 The bit-error-rate

Among of the optical receivers, it said a receiver is to be more sensitive if it gains the same performance with less incident optical power on it. The performance requirement for digital receivers is influenced by the bit-error rate (BER), defined as the possibility of incorrect identification of a bit by the decision circuit of the receiver. A commonly used requirement for digital optical receivers should the BER to be below $1\text{x}10^{-9}$ [25]. The sampled value I occurs fluctuation from start bit to end bit around an average value I_1 or I_0, based on whether the bit represents to 1 or 0 in the bit stream. In the decision circuit, comparison the sampled value with a *threshold value* I_D and bit 1 when $I > I_D$ or bit 0 if $I < I_D$. An error will be occurred if $I < I_D$ for bit 1 because of receiver noises. An error also will be occurred if $I > I_D$ for bit 0. Both of these errors can be contained by defining the error probability as the following equation;

$$\text{BER}= [p(1)P(0/1) + p(0)P(1/0)] \tag{2-5}$$

Where $p(1)$ and $p(0)$ are the probabilities of receiving bits 1 and 0 respectively. Moreover, $P(0/1)$ is the probability of decision 0 when bit 1 is received and $P(1/0)$ is the probability of decision 1 when bit 0 is received. As 1 and 0 bits are equally to occur, $p(1) = p(0) = 1/2$ and the BER is obtained;

$$\text{BER}=\frac{1}{2}[P(0/1) + P(1/0)] \tag{2-6}$$

When the sum of two Gaussian random variables is the same with a Gaussian random variable, the sampled value I has a Gaussian probability density function with variance $\sigma^2 = \sigma_s^2 + \sigma_T^2$. Although both of the average value and the variance are different with bit 1 and 0, I_p is I_1 or I_0 depending on the received bit. When σ_1^2 and σ_0^2 are the corresponding variances, the conditional probabilities are shown by the following;

$$\mathrm{P}(0/1) = \frac{1}{2}\,\mathrm{erfc}\,\left(\frac{\mathrm{I}_1 - \mathrm{I}_\mathrm{D}}{\sigma_1\sqrt{2}}\right) \tag{2-7}$$

$$P(1/0) = \frac{1}{2}\,\mathrm{erfc}\,\left(\frac{I_D - I_0}{\sigma_0\sqrt{2}}\right) \tag{2-8}$$

The complementary error function, *erfc* is defined as;

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty} exp(-y^2)\,dy \tag{2-9}$$

By substituting equations (2.7) and (2.8) into equation (2.6), the BER is given by

$$BER = \frac{1}{4}\left[erfc\,\left(\frac{I_1 - I_D}{\sigma_1\sqrt{2}}\right) + erfc\,\left(\frac{I_D - I_0}{\sigma_0\sqrt{2}}\right)\right] \tag{2.10}$$

Where, an explicit expression for the threshold value I_D is

$$I_D = \frac{\sigma_0\, I_1 + \sigma_1\, I_0}{\sigma_0 + \sigma_1} \tag{2-11}$$

2.8 Optical Fiber

The main function of a transmission channel is to transport the optical signal from the transmitter to receiver with minimum losses in quality as much as possible.

Most terrestrial light wave systems employ optical fibers as the transmission channel because they perform light transmission with low losses as 0.2 dB/km when the carrier frequency is near the spectral region of 1550 nm. The optical fibers are specified in ITU-T with reference to the geometrical, optical, transmission and mechanical attributes such as fiber attributes, cable attributes and link attributes [26].

Fiber attributes are those characteristics that are retained throughout cabling and installation processes. The values specified for each type of fiber can be found in the appropriate ITU-T Recommendation for multimode fiber (Recommendation ITU-T G.651.1) or single-mode fiber Recommendations ITU-T G.652,…,G.657. Chromatic dispersion coefficient is also included in these attributes.

Cable attributes are recommended for cables in factory lengths as they are delivered. The attenuation coefficient and the polarization mode dispersion (PMD) coefficient are included among the cable attributes since they can be affected by the cabling process. Link attributes are characteristic of concatenated cables. A concatenated link usually includes a number of spliced factory lengths of optical fiber cable. Link attributes are affected by factors other than optical fiber cables by such things as splices, connectors and installation. Considering the potential future access network, the requirements for fiber and cabling technologies are essential as shown in Table 2.3.

Table 2.3 Requirements for future access network [27]

Item	Basic requirements	Fiber/cabling technologies
System upgrading flexibility and scalability	Ultra-high speed and long-distance transmission for metro-access convergence Capable of video RF overlay with sufficient quality Expandable to WDM/CWDM system	Low attenuation over wide wavelength range Low polarization mode dispersion (PMD)

Fiber distribution (Flexible design)	Higher utilization efficiency of fiber/equipment	Mid-span access to individual fibers Additional installation on demand
Installation capital expenditure (Capex)	Quick installation Lower labor skill required Inexpensive materials	Mid-span access to individual fibers Additional installation on demand
Maintenance operation expense (Opex)	Secure and easy maintenance Rapid restoration	Easy handling Bendable fiber/cable Easy branching/dropping Adoption of field installable connector or pre-branched/ connectorized cable

As a fiber option based on the standard single-mode fiber (SMF) in accordance with ITU-T G.652, low water peak (LWP) SMF has a low loss characteristic over wide wavelength range from O-band to L-band [28]. It has become popular worldwide for metro and core network systems, while it may also be useful for access network that could adopt full wavelength CWDM system. ITU-T G.652.D was used in this thesis because ITU-T G.652.D is low attenuation and the low water peak fiber allow the possibility of using a larger wavelength range in respect of older fibers, in particular for WDM system applications.

2.9 Optical Fiber Attenuation and Dispersion

Optical fiber attenuation and dispersion are the most considerable parameters of optical fiber communication system.

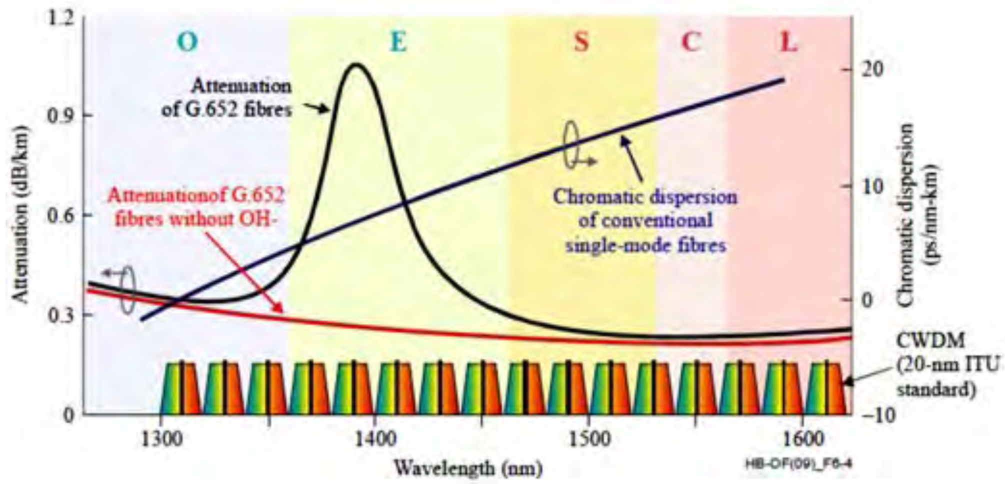


Figure 2-6 SMF attenuation and dispersion curve

2.9.1 Optical Fiber Attenuation

Light traveling in a fiber loses power over distance, mainly because of absorption and scattering mechanisms in the fiber. This loss is referred to as attenuation and measured in decibels per kilometer (dB/km). This is an important property of an optical fiber because together with signal distortion mechanisms, attenuation determines the maximum transmission distance possible between a transmitter and a receiver in a PON without intermediate amplification. The optical signal power at the receiver must have an appropriate level above the signal noise for high-fidelity reception [2].

The attenuation A(λ) at wavelength λ of a fiber between two cross-sections, 1 and 2, separated by distance *L* is defined, as:

$$A(\lambda)=10\log\frac{P_1(\lambda)}{P_2(\lambda)}\ (\mathrm{dB}) \tag{2.12}$$

Where;

$P_1(\lambda)$ is optical power traversing the cross-section 1, and

$P_2(\lambda)$ is optical power traversing the cross-section 2 at the wavelength λ.

For a uniform fiber, it is possible to define attenuation per unit length, or an attenuation coefficient which is independent of the length of the fiber:

$$\alpha(\lambda)=\frac{A(\lambda)}{L}\text{ (dB/unit length)} \tag{2.13}$$

The attenuation coefficient depends on the wavelength of transmitted light [26].

2.9.2 Optical Fiber Dispersion

The information-carrying capacity is limited by various signal dispersion factors in the optical fiber. The three main dispersion categories are modal, chromatic, and polarization mode dispersions. These distortion mechanisms cause optical signal pulses to broaden as they travel along a fiber. Figure 2.6 shows that as optical pulses travel in a fiber, they broaden due to dispersion.

1) Modal dispersion: Modal dispersion arises from the different path lengths associated with various modes (as represented by light rays at different angles). It appears only in multimode fibers, since in a single-mode fiber there is only one mode.
2) Chromatic dispersion (CD): It is the spreading of a light pulse in an optical fiber caused by the different group velocities of the different wavelengths composing the source spectrum. Group delay is the time required for a light pulse to travel a unit length of fiber. The group delay as a function of wavelength is denoted by $\tau(\lambda)$. It is usually expressed in ps/km. Chromatic dispersion coefficient is the change of the group delay of a light pulse for a unit fiber length caused by a unit wavelength change. Thus, the chromatic dispersion coefficient is $D(\lambda)=d\tau/d\lambda$. It is usually expressed in ps/nm • km. Chromatic dispersion slope is the slope of the chromatic dispersion coefficient versus wavelength curve. The dispersion slope is defined as $S(\lambda) = dD/d\lambda$. Zero-dispersion wavelength is the wavelength at which the chromatic dispersion vanishes. Zero-dispersion slope is the chromatic dispersion slope at the zero-dispersion wavelength. At 2.5 Gbps, CD is not an issue. However, lower data rates are seldom desirable. But at 10-Gbps, it is a big issue and the issue gets even bigger at 40-Gbps.
3) Polarization mode dispersion (PMD): It is related to the differential group delay (DGD), the time difference in the group delays between two orthogonal polarized modes, which causes pulse spreading in digital systems and distortions in analogue systems. In ideal circular symmetric fibers, the two

polarization modes propagate with the same velocity. However, real fibers cannot be perfectly circular and can undergo local stresses; consequently, the propagating light is split into two polarization modes.

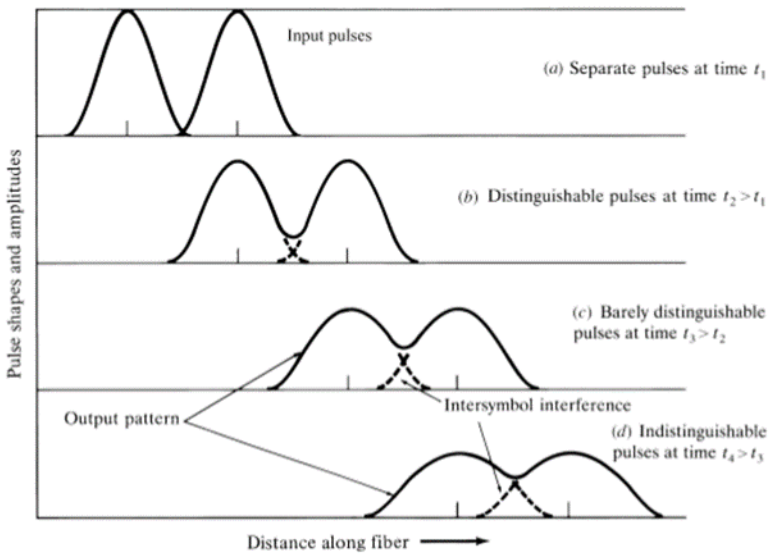


Figure 2-7 Progressive broadening pulses traveling along a fiber [2]

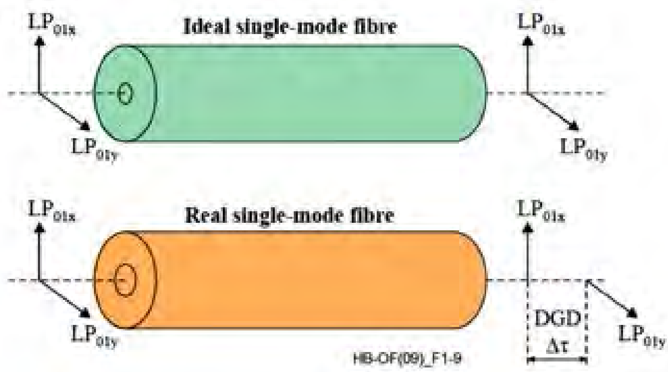


Figure 2-8 The two polarization modes propagating at different velocities [26]

Another source of signal distortion because of the nonlinear effects is related to the intensity of silica refractive index. Although most nonlinear effects are relatively weak for silica fibers, they can accumulate to significant levels when many optical amplifiers are cascaded in series to form a long-haul system. Nonlinear effects are especially important for undersea light-wave systems for which the total fiber length can approach thousands of kilometers [2].

Table 2.4 Attenuation and dispersion parameters of ITU-T G 652.D SMF for16 CWDM wavelengths [14]

Wavelength (nm)	Attenuation (dB/km)	Dispersion (ps/nm.km)
1271	0.385	-4.300
1291	0.370	-2.100
1311	0.350	-0.093
1331	0.340	1.730
1351	0.320	3.473
1371	0.300	5.143
1391	0.320	6.744
1411	0.275	8.283
1431	0.243	9.761
1451	0.225	11.185
1471	0.213	12.557
1491	0.203	13.882
1511	0.196	15.161
1531	0.191	16.399
1551	0.190	17.597
1571	0.192	18.758

2.10 Modulation Formats

Before the source light can be launched into the communication channel, the information that needs to be transmitted should be imposed on it. This step is accomplished by an optical modulator in Figure 1.5. The modulator uses the data in the form of an electrical signal to modulate the optical carrier. Although the external modulation is needed for the high bit rates, it can be dispensed with at low bit rates using a technique known as direct modulation [24]. The desire for higher per-fiber transport capacities and, at the same time, the drive for lower costs per end-to-end transmitted information bit has led to optically routed networks with high spectral efficiencies. Among other enabling technologies, advanced optical modulation formats have become key to the design of modern wavelength division multiplexed (WDM) fiber systems. In the optical communications community, all formats that go beyond On/Off Keying (OOK) have therefore earned the qualifier advanced.

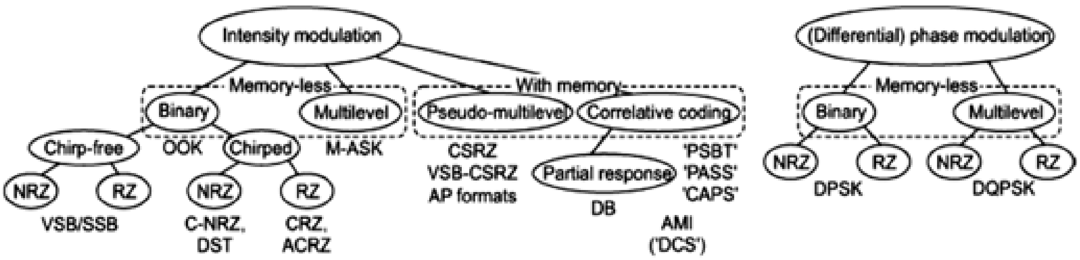


Figure 2-9 Classifications of the intensity and phase modulation formats [29]

In single-mode optical fibers, the optical field has three physical attributes that can be used to carry information: intensity, phase (including frequency), and polarization. Depending on which of the three quantities is used for information transport, we distinguish between intensity, phase (or frequency), and polarization data modulation formats (DMFs) [29]. Various modulation formats have been used in WDM communication systems. They have two key features: the way the data are represented in the optical signal, and the keying technique. For example, in intensity modulated systems the data are represented by the intensity of the optical signal and in phase shift keying (PSK) by the phase. The keying alternatives are known as non-return-to-zero (NRZ) or return-to-zero (RZ). In the former case, the information-bearing signal occupies a full bit period, whereas in the latter case the information is contained in a pulse occupying less than the full bit period. Each can incorporate various data representations. For example, OOK is an intensity modulation representation that involves turning the transmitter power on for a 1 and off for a 0. It can be implemented either as NRZ or RZ. Comparing the two, RZ occupies more bandwidth than NRZ because the pulses are narrower, and RZ has a higher peak power than an NRZ signal running at the same average power level.

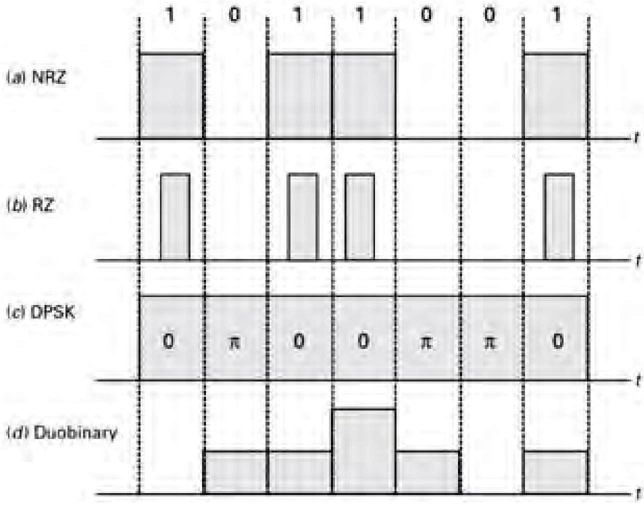
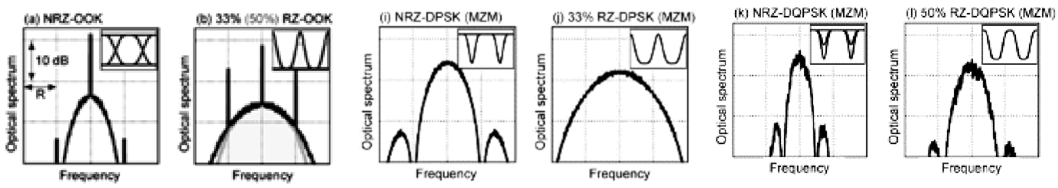


Figure 2-10 Modulation Formats [30]

In DWDM systems, the interplay of dispersion and nonlinear effects may or may not favor RZ over NRZ, depending on bit rates. At moderate speeds (10–20 Gbps) in dispersion-managed systems with alternating positive and negative dispersion fibers, RZ tends to perform better than NRZ, because the latter is more affected by nonlinearities. At higher speeds (40 Gbps) NRZ tends to perform better, because the larger bandwidth occupied by the RZ pulse makes it more vulnerable to dispersion. However, the situation is more complicated than this. If the modulation depth is high, then the spectrum is narrowed, and under those conditions RZ outperforms NRZ at high speeds at transoceanic distances. NRZ-differential phase-shift keying (NRZ-DPSK) and RZ-DPSK are alternative modulation formats that offer certain advantages compared to the traditional OOK formats. In conventional PSK, the phase of the carrier is modulated at the transmitter and at the receiver phase-to-intensity conversion is needed before the signal reaches the photodetector, because the photo-detection process is phase insensitive. This can be done in a coherent optical system [30].

1) Return-to-Zero On/Off Keying (RZ-OOK) transmitters can be implemented either by electronically generating RZ waveforms, which are then modulated onto an optical carrier, or by carving pulses out of an NRZ signal using an additional modulator, called pulse carver. The other modulation formats are as follows:

2) Nonreturn-to-Zero On/Off Keying (NRZ-OOK) is the simplest way to generate optical modulation format is NRZ-OOK, often just referred to as NRZ. It is most conveniently used at bit rates of 10 Gbps and above.
3) Differential binary PSK (DBPSK, or simply DPSK) encodes information on the binary phase change between adjacent bits: a 1-bit is encoded onto a π phase change, whereas a 0-bit is represented by the absence of a phase change. Like OOK, DPSK can be implemented in RZ and NRZ format. The main advantage from using DPSK instead of OOK comes from a 3-dB receiver sensitivity improvement.
4) DQPSK is the only true multilevel modulation format (more than one bit per symbol) that has received appreciable attention in optical communications so far It transmits the four phase shifts (0, +π/2, -π/2, +π) at a symbol rate of half the aggregate bit rate. As in the case of DPSK, a DQPSK transmitter is most conveniently implemented by two nested Mach–Zehnder modulators (MZMs) operated as phase modulations. Unlike Electro-absorption Modulators (EAMs), which work by the principle of absorption, MZMs work by the principle of interference, controlled by modulating the optical phase [29].



(a) (b) (c)

Figure 2-11 Optical spectra and optical intensity eye diagrams of important modulation formats [29]

2.11 Optical Orthogonal Frequency Division Multiplexing (OFDM)

The use of OFDM to form a super-channel appears into two categories: (1) OFDM-based modulation, which naturally realizes a square-like signal spectral shape to allow close packing of multiple modulated signals, and (2) coherent optical (CO)-OFDM-based carrier multiplexing, which enables seamless multiplexing of modulated signals [31]. The transmission for higher data rate demands for the increase in the useable bandwidth of a transmission media. Nevertheless, at present, the available bandwidth of optical single-mode fiber is limited about 12.5 THz over C and L bands. Therefore, in order to achieve the highest bandwidth efficiency, there are several approaches that have been proposed. The first era is the DWDM with the channel spacing of 25 GHz with the data rate per channel of 10 Gbps modulated by the on-off keying format. At that time, we can further increase the bandwidth efficiency by using the noncoherent modulation format such as DQPSK. Then, the noncoherent optical OFDM has been studied since it can reduce the channel spacing equals to the Nyquist frequency. Afterward, the coherent detection, incorporated with the use of either n-QAM or m-PSK, has been debuted. Moreover, applying the polarization-division multiplexing (PDM) and the dispersion compensation by electrical digital signal processing (DSP), we can enhance the bandwidth efficiency to be more than double. In order to increase the bandwidth efficiency, currently the Nyquist-WDM (N-WDM) and the coherent optical OFDM (CO-OFDM) are very attractive. Both two schemes realize the channel spacing that is identical to the Nyquist frequency. However, the sub-carriers in CO-OFDM signal exhibit the Sinc-function shape. Therefore, they are overlapped with keeping the orthogonality. On the other hand, the N-WDM signal in time domain exhibits the Sinc-function shape, all channel spectrums exhibit the rectangular shape, and can be allocated closed among each other without inter carrier interference. With the combination of the advance modulation formats, the PDM, and either CO-OFDM or N-WDM, the bandwidth efficiency drastically improves. Comparing with the N-WDM, the CO-OFDM has been proved to have greater tolerance of the fiber nonlinearity and fiber dispersion than the N-WDM [32].

In fact, subscribers always require different data rate *s* for different services. This leads to the concept of the flexible network, which can allocate bandwidth to single subscriber for different services by dynamically bonding different number of channels, which is called the super-channel. When the CO-OFDM signals are used to form a super-channel, the transmission of CO-OFDM signal with the total data rate of 1 Tbps beyond 8,000 km has been reported in [33]. In [34], a super-channel with the total data rate of 7.5 Tbps, formed by 4 x 1.875 CO-OFDM signals, has achieved the transmission distance over 1,280 km. Recently, the self-coherent detection method for a super-channel with the total data rate of 8 Tbps, formed by 4 x 2 Tbps CO-OFDM signals, is presented in [35].

2.12 Super-channels

The growth in the internet is demanding additional bandwidth scale without increasing operational complexity, and asking the question for beyond 100 Gbps, one answer is a super-channel, an evolution in DWDM in which several optical carriers are combined to create a composite line side signal of the desired capacity, and which is provisioned in one operational cycle. Moreover, it must be possible to implement super-channel technology using existing DWDM engineering techniques, without requiring longer term technology advances. There are two obvious implementation options for developing single-carrier transponders that operate at data rates above 100 Gbps. One is to transmit more modulation symbols per second and the other is to encode more bits into a modulation symbol (or some combination of the two). Super-channel technology adds a third option—the ability to treat multiple carriers as a single operational unit. For simplicity, this description will assume that a 1Tb/s unit of capacity is required [36]. Significant progress has been witnessed in the research area where 1 Tbit/s and beyond super-channel transmissions over several thousands of kilometres of fibre have been demonstrated during the past few years [1, 2]. To detect the superchannel signal, the wideband signal has to be divided into multiple subbands, which are then recovered individually. As a result, large amounts of laser sources are required to perform as local oscillators (LOs) for Tbit/s coherent detection, which may greatly increase the system complexity and cost [35].

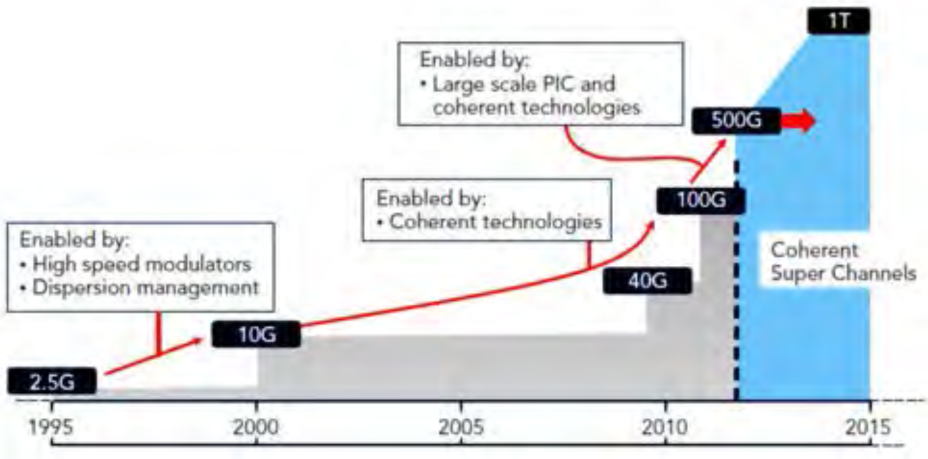


Figure 2-12 The technology enablers for DWDM capacity [37]

The move to 10 Gb/s wavelengths was enabled by higher performance optical modulators, and also by a better understanding of chromatic dispersion management and the availability of dispersion compensating fibers.1 However, the same simple modulation format was used at both 2.5 Gb/s and 10 Gb/s. This modulation technique is Intensity Modulation with Direct Detection (IM-DD); also known as On/Off Keying (OOK) and Non-Return to Zero (NRZ). IM-DD has served the industry well, but it is no longer particularly efficient in spectrum utilization, and is very susceptible to fiber impairments, such as chromatic dispersion (CD) and polarization mode dispersion (PMD), as the data rate increases beyond 10 Gb/s. As shown in Figure 2.8, the technological breakthrough that allowed the “10G Speed Limit” to be broken was the introduction of coherent optical technologies, initially for 40Gb/s and soon after for 100Gb/s long haul transmission. However two things helped bring coherent back to the table. First is that the high order modulation used by coherent technologies offers much greater spectral efficiency than IM-DD. Second is that coherent technologies include powerful digital signal processing that help to solve the problem of chromatic and polarization mode dispersion suffered by IM-DD systems above 10G, and thereby deliver vastly increased capacity over the same, or even better distances. Phase shift keying modulation, such as Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK) were favored because, in the case of DPSK, there is a significant advantage in the required optical signal to noise ratio (OSNR) as compared to IM-DD [37].

2.13 Switching Technology

Early concepts of a wavelength-based fiber-optic switch integrated a digital microelectromechanical systems (MEMS) technology into a fiber optic spectrometer [38]. This was extended to 2-D MEMS mirrors [39] and started commercial development about 15 years ago, using digital MEMS, analog MEMS, and liquid crystal (LC) [40] switching technologies.

2.13.1 Wavelength Selective Switch (WSS)

The wavelength-selective switch (WSS) is a switch that can select or receive wavelengths as required by the subscriber. WSS can dynamically route, block and attenuate all DWDM wavelengths within a network node. WSS has undergone significant development recently to address reconfigurable optical add/drop multiplexer (ROADM) applications in multi-wavelength optical networks. The ROADM is a commercial application that allows software-controlled transparent optical switching of wavelength channels into and out of a fiber in an optical network [10].

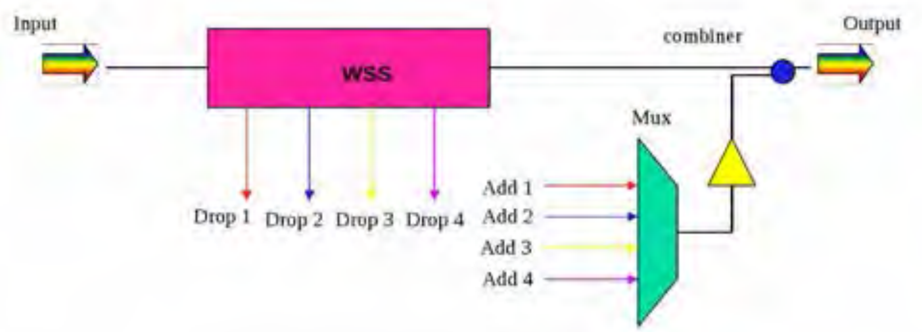


Figure 2-13 Schematic diagram for Wavelength Selective Switch

The ROADM application is particularly valuable because denser wavelength-division multiplexing (DWDM) networks are deployed extensively in metropolitan networks, which have a many number of wavelengths and a bandwidth demand that is relatively large and unpredictable even with sophisticated network planning. The ROADM is valuable in this type of network by adding the flexibility in software to "express" individual channels through a node or to "add" and "drop" a wavelength for information access or rerouting along another path in the network. The WSS has become the most widely used optical switch for this application, because it is a very cost-effective and scalable technology, which is also among the most flexible solutions from an optical networking perspective.

2.13.2 Optical Switching Characteristics

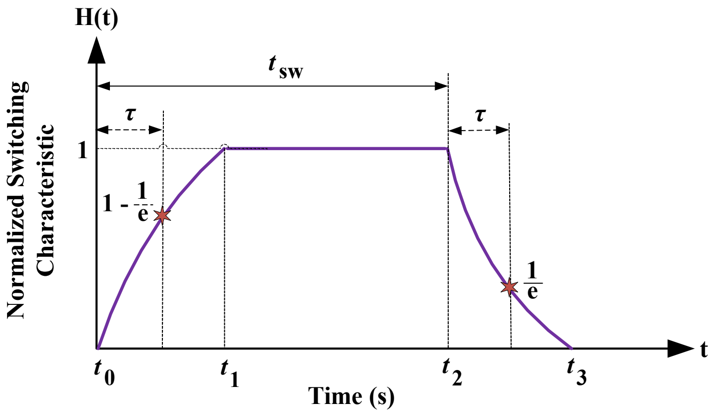


Figure 2-14 Switching characteristic curve of a switch

The transfer function of switching characteristic can be calculated as the following equation and the curve is as shown in figure 2.13 [41];

$$H(t) = [1 - \exp(-\frac{t-t_0}{\tau})\Big|_{t_0 < t \le t_1} + 1\Big|_{t_1 < t \le t_2} + \exp(-\frac{t-t_0}{\tau})\Big|_{t_2 < t \le t_3}]\exp(j\theta) \qquad (2.14)$$

Where,

$H(t)$ = switching transfer function

τ = time constant (s)

t_0 = the time that the switch starts to switch from the original output port to the next outgoing port (s)

t_1= the time that the response of the switch at the output port is 100% (s)

t_2= the time that the switch starts to switch from the outgoing port to another output port (s)

t_3= the time that the signal is shifted to the output port after completion of switching process (s)

t_{sw}= switching time (s)

The switching characteristic of the switch is divided into three phases as follow [41] [42];

1) The time interval $t_0 < t \leq t_1$: the time that the switch starts to switch from the original output port to the outgoing port until the response of the switch at the output port is 100%. That is, the startup circuit starts at signal 0 until the peak point is 1 at time t_1.
2) The time interval $t_1 < t \leq t_2$: the time that the response at the output port is determined to be 100% until the switch starts to switch from the output port to another port. That is, the switching process is still active where the signal strength remains 1 until the point at time t_2.
3) The time interval $t_2 < t \leq t_3$: the time that the switch starts to switch from the outgoing port to another output port until the signal is switched to the outgoing port so that the switching process will be completed. The signal strength was dropped from the maximum signal strength of 1 to 0 level.

The conditions of switching characteristics that depend on time constant (τ) are shown as the following;

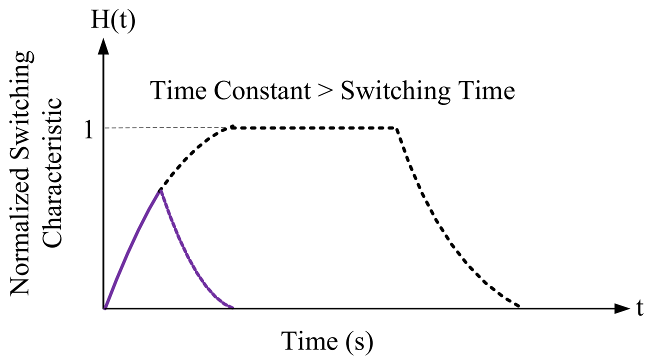


Figure 2-15 The condition with time constant is greater than switching time

The condition with the time constant is greater than the switching time is shown in Figure 2.14. In this condition, the switching operation is not effective because the rising time of the first switch is not reached to the highest point and drop off. Although the switching operation is continued to the next switch, it is not enough to send the signal for the first switch.

The condition with time constant is less than or equal to the switching time is shown in Figure 2.15. The switching operation is effective to send the signal but the signal will be distorted between the falling time of the first switch and rising time of the next switch because of overlapping. Therefore, the signal strength is gradually decreased according to the switching characteristic of the switch that will be focused on this study. Moreover, the relation of the time constant and switching time should be the condition of time constant is less than or equal to the switching time for the effective switching operation.

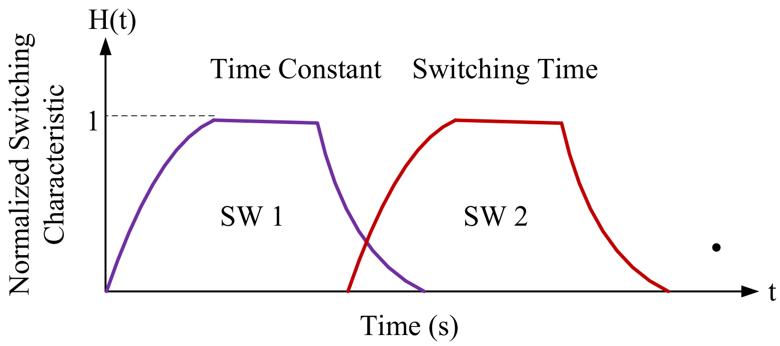


Figure 2-16 The condition with time constant is greater than switching time

Therefore, the bit rate of output signal E_{out} (Gbps) after switching will be obtained by multiplying the switching transfer function *H(t)* with the bit rate of input signal E_{in} (Gbps) as the following equation;

$$E_{out} = E_{in} \times H(t) \tag{2.15}$$

The detail of switching characteristics and methodology of WSSs in proposed system were discussed in CHAPTER 3.

CHAPTER 3
SYSTEM DESIGNS AND METHODOLOGY

The system configuration and methodology of improving system performance based on switching characteristics of WSSs with proper delay time are discussed in this chapter.

3.1 System configuration

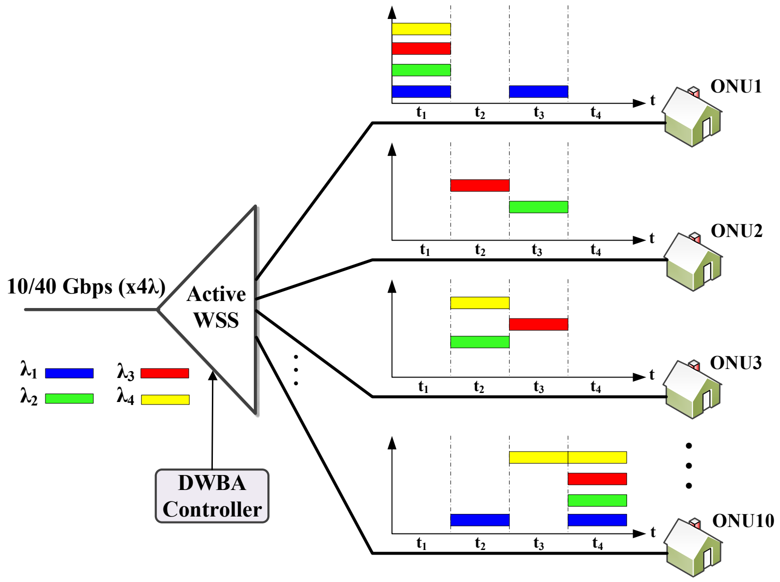


Figure 3-1 The configuration of 10/40 Gbps per wavelength system

Figure 3.1 shows the configuration of flexible FTTx system designs using active WSS incorporated with DWBA. The data rates for the two system designs are 10 Gbps/λ and 40 Gbps/λ. The wavelengths used in the network are in the range of 1271-1571 nm CWDM with 20 nm channel spacing. The system employs the WSS to assign the appropriate number of wavelength for each subscriber as requested. Therefore, the maximum data rates per subscriber are 40 Gbps and 160 Gbps for the two system designs. In these FTTx system designs, WSS can be used instead of passive WDM de-multiplexers used in WDM-PON systems for downlink operation. WDM signals composed of different number of CWDM wavelengths on different time intervals are generated from the optical line terminal (OLT), which is controlled by DWBA under the dynamic requests for data rates from optical network units (ONUs) installed at subscriber end points. It should be noted that the response for the different requests in data rates from ONUs can be performed by allocating the appropriate number of wavelength to different ONUs.

As the system operation of DWBA, if the ONU1 requests a data rate of 40 Gbps in the time interval t_1, the OLT will allocate all wavelengths to the ONU1. After receiving the requested data rate from ONU1 in time interval t_1 and then all wavelengths will be returned to the OLT to be allocated a new wavelength in time t_2. For time interval t_2. if ONU1 does not request a data rate, no wavelength is sent to ONU1 during time interval t_2, but we will see that DWBA allocates 1 wavelength to ONU2 and 1 wavelength to ONU4 and 2 wavelengths to ONU3 because ONU2 and ONU4 request 10 Gbps data rate while 20 Gbps data rate is requested from ONU3. DWBA allocates one wavelength for each ONUs during time interval t_3 because all ONU request 10 Gbps data rate. In time interval t_4, all wavelengths will be allocated in ONU4 when ONU4 requested a 40 Gbps data rate. For 40 Gbps/λ system, the function of the DWBA is the same as described above but the maximum data rate will be 160 Gbps. It can be clearly seen that how many ONUs are connected to the same port with the OLT is not relying upon the number of wavelengths in the FTTx system.

3.2 System simulation set up

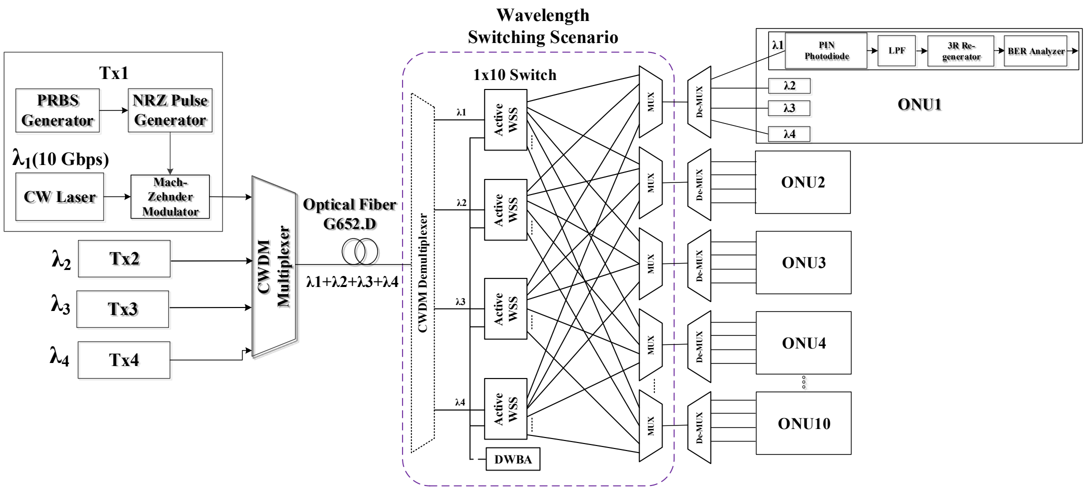


Figure 3-2 Simulation set up for 10 Gbps/λ system with NRZ-OOK modulation format.

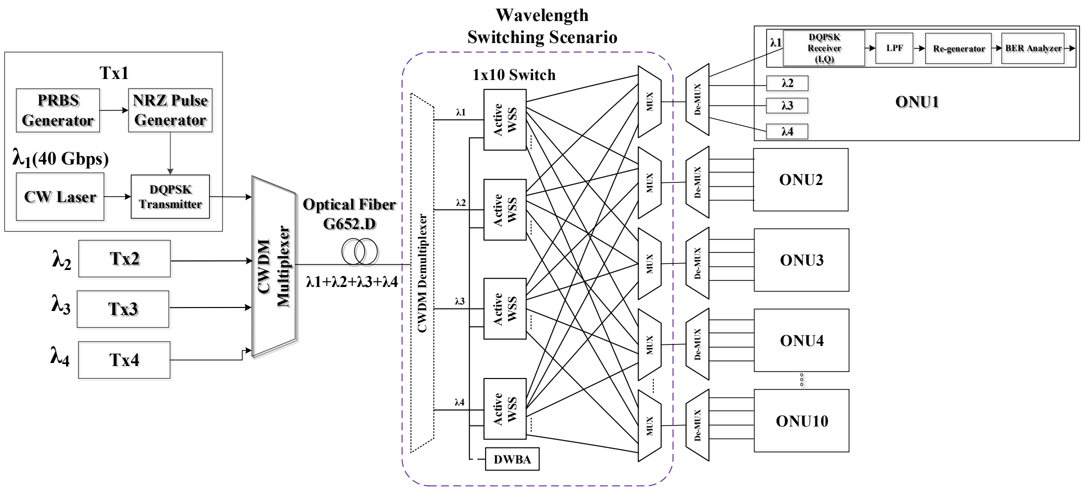


Figure 3-3 Simulation set up for 40 Gbps/λ system with NRZ-DQPSK modulation format.

For the system simulation set up, the required parameters and 3 different types of WSS are as shown in table 3.1 and 3.2. In this system, the nonlinear effect will be neglected because of just considering short distance access network. The signal with 10/40 Gbps/λ is transmitted through SMF ITU-T G.652.D fiber and is switched by WSS, which is also controlled by a DWBA controller. The study is only considered with the maximum fiber length of 20 km with the related attenuation and dispersion parameters for both systems. The number of wavelengths that are connected to the OLT is limited by 4 channels (1471nm-1531nm) for both systems. The 4 CWDM wavelengths are generated by the continuous wave (CW) laser array and sending the signal from OLT as the 4 wavelength to 10 ONUs system represent the wavelengths 1471, 1491, 1511, and 1531 nm, expressed in terms of frequencies: 203.8, 201.1, 198.4 and 195.8 THz, respectively.

In this thesis, the DWBA controller is created by MATLAB program as randomly switching sequences to be active WSSs. It should be noted that the response for the different requests in data rates from ONUs can be performed by allocating the appropriate number of wavelength to different ONUs. The simulation parameters of SMF and several types of WSS [42] [43] [41] [44] that used in this study are shown in table 3.1 and 3.2.

Table 3.1 The 3 different types of WSS with related parameters [44] [43]

Types of WSS	Time constant(τ)	Insertion Loss
Photonic crystal switch	0.5 ps	16 dB
GaInAs/InP multiple quantum well switch (MQW)	100 ps	16 dB
Electro-optic switch	5ns	2 dB

Table 3.2 Attenuation and dispersion coefficients of G652.D SMF with related wavelengths and other simulation parameters

Items	Applications	Max Values	Units	Ref.
Attenuation coefficient of SMF	1471 nm 1491 nm 1511 nm 1531 nm	0.213 0.203 0.196 0.191	dB/km	[45]
Dispersion coefficient of SMF	1471 nm 1491 nm 1511 nm 1531 nm	12.557 13.882 15.161 16.399	ps/km-nm	[45]
P_{TX}	Transmitted power	9	dBm	
MUX/DE-MUX	Insertion loss	1.5	dBm	
PIN photodetector	Responsivity	0.9(90%)	A/W	
	Dark current	10	nA	
	Thermal noise	18.1381×10^{-12}	A/Hz^0.5	

Previously, the first study has proposed the FTTx system using an active WSS with a dynamic wavelength and bandwidth allocation, in order to improve bandwidth utilization since the WSS is able to transmit signal to any subscribers with different data rate as the requirements of subscribers. The computer simulation results based on data rate of 10 Gbps/λ, demonstrate the feasibility of the transmission of 160-Gbps signal (16 CWDM wavelengths:1271-1571nm) to a single subscriber over the maximum reaches without considering switching effects [46]. However, the next study has discovered the effect of switching characteristics of WSS is the main factor that affect to the bit-error rate (BER) of signal transmission of the system. Therefore, the study has demonstrated with the two system designs based on the data rate of 10 Gbps/λ. The computer simulation results were shown the maximum reaches of the transmission of 40-Gbps signal (4 CWDM wavelengths: 1471-1531 nm) to 10 subscribers, and the 80-Gbps signal (8 CWDM wavelengths: 1431-1571 nm) to 5 subscribers which are limited by the different types of WSSs switching characteristics [47]. Moreover, considering the switching effects of WSSs, the signal distortion due to the overlapping period when WSSs switched from current subscribers to next subscribers causes the switching crosstalk among the subscribers. Therefore, the study also has conducted to reduce and overcome the signal distortion by adding the proper delay time for different types of WSS. The simulation results show that the signal bit-error rate varies with the proper delay time $x\tau$ of WSS in that study [48].

3.3 Signal distortion reduction scenario

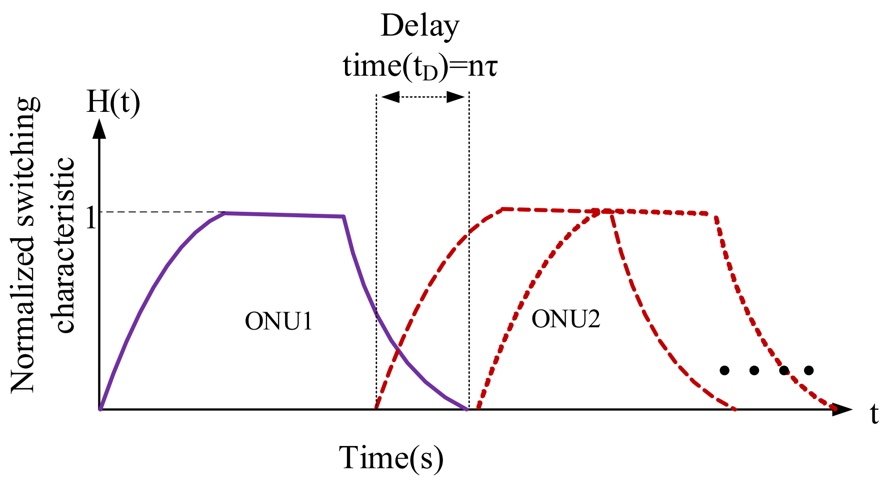


Figure 3-4 Reduction of signal distortion by adding proper delay times in WSS switching characteristics of the system.

For the switching characteristics of WSS without considering of the delay time(t_D), when WSS switches the signal from ONU1 to ONU2, the signal falling time for ONU1 overlaps with the signal rising time for ONU2 and then that will lead to the signal distortion in time domain. Therefore, in order to overcome the signal distortion problem due to overlapping period, the several delay time(t_D) in n time of time constant(τ) is added. After the delay time is added, the switching characteristic of ONU2 is shifted for $n\tau$ in time domain as shown in dash line. The received optical power can be obtained from simulation results and but the BER cannot be directly obtained from eye diagrams from the simulation because of randomly switching sequences. The BER can be calculated from the equations; (2-1) to (2-11). The fiber attenuation and dispersion parameters have to be considered in this study but non-linear effect is neglected because of short distance transmission.

3.4 Problem statements

As signal distortion reduction methodology, in order to improve the transmission signal strength, we will add the delay times in characteristics of WSS. In this study, since we only investigate the simulation results applied with the proper delay times: $t_D=1\tau,2\tau,3\tau,4\tau$, the results are not still exact values as optimal delay time. If we can approach to find the optimal delay time combining with the mathematical model, the results will be more accurate.

For 40 Gbps/λ system, we do not obtain the BER values directly from the eye diagrams of simulation because the DWBA controller can generate only randomly the switching sequences. Therefore, we can calculate the BER values from the equations 2.1 – 2.11.

CHAPTER 4
PRESENTATION OF RESULTS

The results presentation is expressed in this chapter. Moreover, the two-transmission system designs 10, 40 Gbps per wavelength data rate with 4 wavelengths to 10 ONUs by using 3 types of WSSs are also presented.

4.1 The switching characteristics of 3 different types of WSS with proper delay times for 10 Gbps/λ data rate

In this system, all 4 wavelengths are transmitted the signal with the 10 Gbps data rate per wavelength to 10 ONUs by using computer simulations with Optisystem software version 10.0. The structure of this system is shown in Figure 3.2 consisting of 4 CWDM wavelengths in the range of 1471nm-1531nm and channel spacing is 20 nm. The 4 wavelengths are generated by the source of continuous wave (CW) laser array. The electrical signal is generated by the Pseudo-random bit sequence generator (PRBS) randomly. The randomness signals are sent to the NRZ pulse generator and then modulated by Mach-Zehnder modulator with a data rate of 10 Gbps per wavelength. After that, all of them are combined in a multiplexer with an insertion loss of 1.5 dB. The signal of each wavelength is transmitted through the 20 km length ITU-T G.652.D SMF optical fiber.

The differential group delay for polarization mode dispersion (PMD) value is 0.2 ps/km. The effect of non-linear for all 4 wavelengths is neglected because of short distance transmission. After passing through the signal along the fiber, the signals are separated by demultiplexer with insertion loss value of 1.5 dB to the wavelength selective switches. The DWBA controller device will provide wavelength allocation to each subscriber with a switch. There are 3 types of active wavelength selective switches for this study as shown in Table 3.1. Each type of WSSs has different time constants that related in switching characteristics of each switches. After switching the signal by WSSs, it goes through the multiplexer again to merge the signal before sending it to the receiver. Each wavelength is adjusted to the value of the attenuation coefficient with optical attenuator and it was detected by a PIN photodetector with the parameters of 0.9 A/W receiver responsivity, 10 nA of receiver dark current and 18.1381×10^{-12} A/Hz^0.5

of thermal noise. And then the low frequency electrical signals are filtered out by low-pass filter circuit with cutoff frequency of (0.75 x bit rate) [Hz]. The 3R Regenerator is the last device to send the detected signal to the eye-diagram analyzer.

As already mentioned in section 3.3, the signal distortion will be occurred when the switching cycle is overlapped by each other because of delay time effect. In order to study the performance of the system, we simulate the flexible FTTx system with 3 several different types of WSS based on data rate of 10 Gbps/λ when the maximum reach is limited to 20 km and the maximum signal transmit power is 9 dBm. As the number of transmitted channel is limited to 4 CWDM wavelengths in this study, 4 numbers of WSSs will be used in the simulation to assign the wavelengths as dynamically requested from ONUs. All the simulations are performed by the commercial OptiSystem software version 10. The Following are the results of the relation between received optical power(P_R) and log(BER) for 3 several different types of WSS with proper delay time(t_D=nτ,n=0,1,2,3,4). The performance of the system is evaluated in term of received optical power(P_R) for the worst case under the limitation of BER=10^{-4} (with FEC).

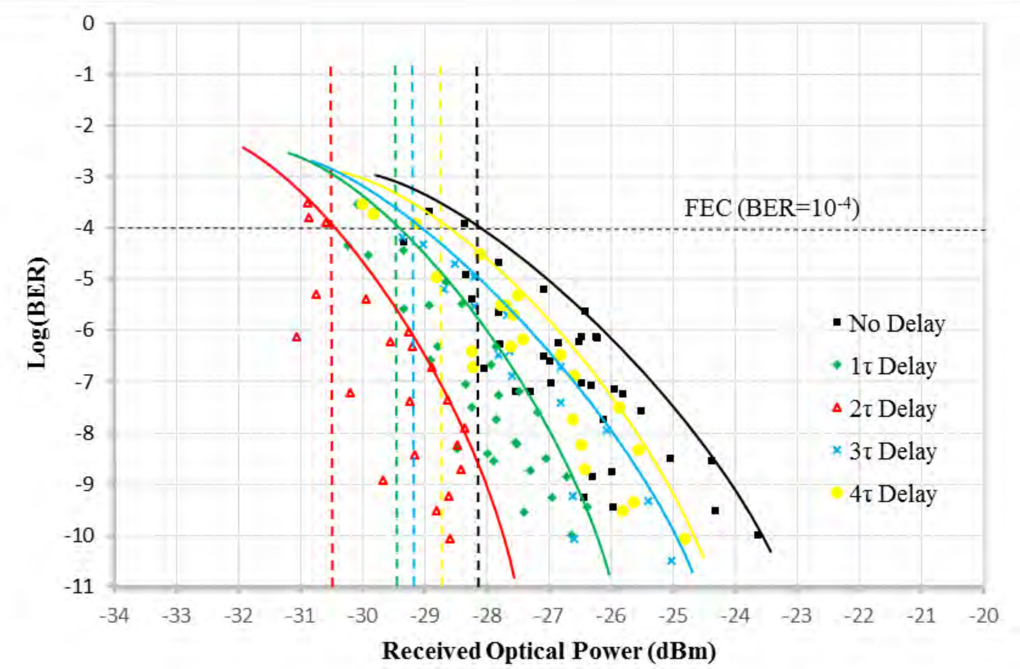


Figure 4-1 The relation between received optical power and Log(BER) for the 10Gbps/λ system using photonic crystal switch(τ = 0.5 ps) with the proper delay times(nτ, n = 0,1,2,3,4).

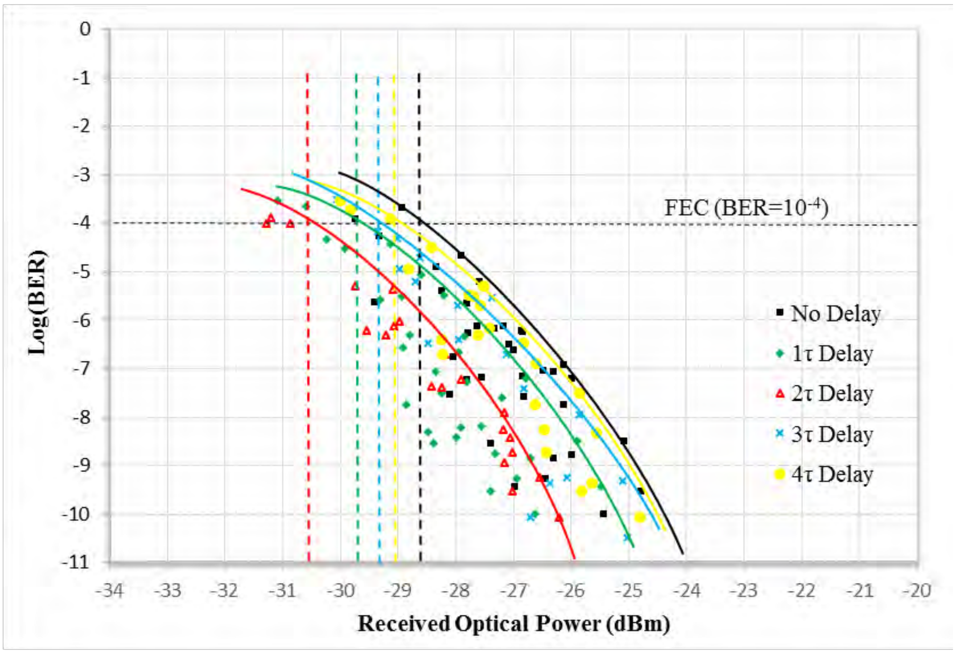


Figure 4-2 The relation between received optical power and Log(BER) for the 10Gbps/λ system using MQW switch(τ = 100 ps) with the proper delay times($n\tau$, n = 0,1,2,3,4).

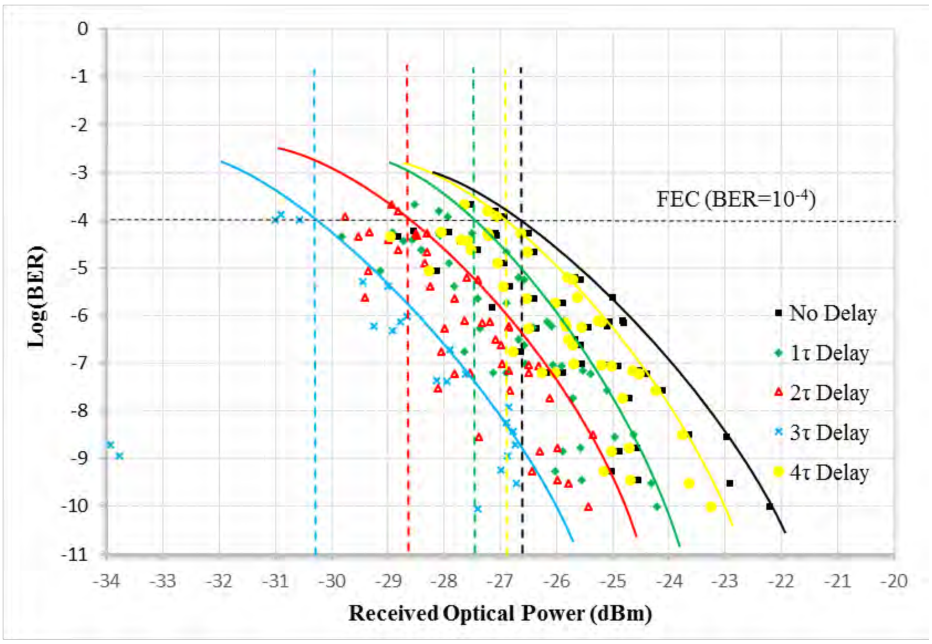


Figure 4-3 The relation between received optical power and Log(BER) for the 10Gbps/λ system using electro-optic switch(τ = 5 ns) with the proper delay times($n\tau$, n = 0,1,2,3,4).

Figure 4.1 - 4.3 show the relation between log(BER) and received optical power(P_R) by using the photonic crystal switch, the MQW switch and the electro-optic switch with the proper delay time(t_D=nτ,n=0,1,2,3,4) respectively. As the simulation results, the P_R for the system by using photonic crystal switch without delay time is -28.21 dBm and the others are -29.43 dBm, -30..43 dBm, -29.23 dBm and -28.94 dBm for using 1τ, 2τ, 3τ, 4τ delay time. And then, for the MQW switch, the P_R for the system by using without delay time is -28.59 dBm and -29.67 dBm, -30.57 dBm, -29.32 dBm,-29.12 dBm are the others P_R for using 1τ, 2τ, 3τ, 4τ delay time. As the last, for the electro-optic switch, the received optical power for the system by using electro-optic switch without delay time is -26.72 dBm and -27.45 dBm, -28.63 dBm, -29.58 dBm,-26.82 dBm are the others P_R for using 1τ, 2τ, 3τ, 4τ delay time. To sum up, for the photonic crystal switch and the MQW switch without delay time, the simulation results show the P_R for both switches are almost the same which are -28.21 dBm and -28.59 dBm respectively. When we applied 2τ delay time for these two switches, the system P_R can be achieved the improvement of -30.43 dBm and -30.57 dBm respectively of course the power budgets can be improved with 2.22 dB and 1.98 dB respectively. On the other hand, the electro-optic switch without delay time system has P_R = -26.72 dBm and but however P_R is increased to -29.58 dBm after using 3τ delay time of course the power budget is improved about 3dB (2.86 dB). Table 4.1 summarizes all of the received optical power for the system by using 3 different types of WSS with proper delay times.

Table 4.1 P_R of the system by using proper delay times(nτ, n = 0,1,2,3,4) for 3 different types of WSS.

Types of WSS	**Received Optical Power(P_R) at BER=10^{-4}(with FEC)**				
	No Delay	1τ Delay	2τ Delay	3τ Delay	4τ Delay
Photonic crystal switch(τ=0.5ps)	-28.21 dBm	-29.43 dBm	-30.43 dBm	-29.23 dBm	-28.94 dBm
MQW switch(τ=100ps)	-28.59 dBm	-29.67 dBm	-30.57 dBm	-29.32 dBm	-29.12 dBm
Electro-optic switch	-26.72 dBm	-27.45 dBm	-28.63 dBm	-29.58 dBm	-26.82 dBm

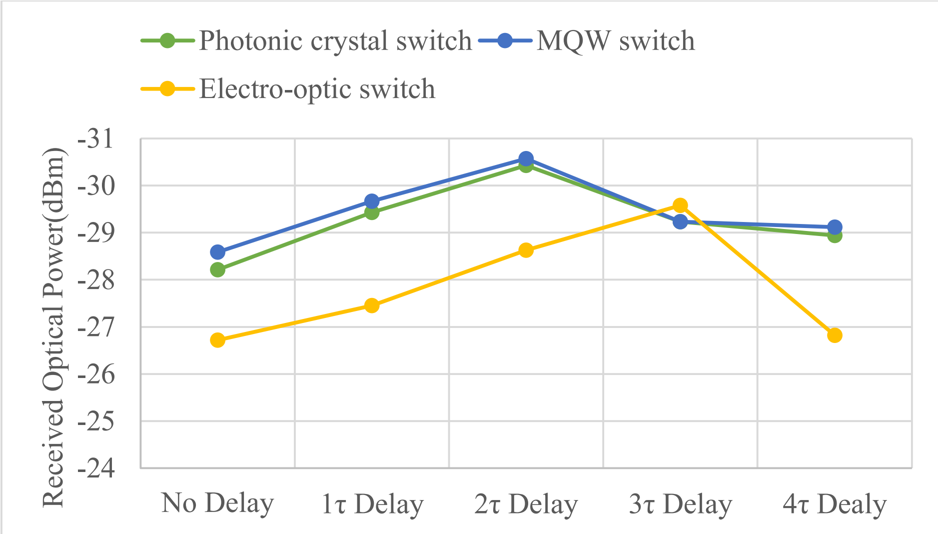


Figure 4-4 The relation between P_R and the proper delay times(nτ, n = 0,1,2,3,4) for 10Gbps/λ system.

Table 4.2 The system power budget improvement using 3 different types of WSS applied with proper delay times(nτ, n = 1,2,3,4)

Types of WSS	**Power Budget improvement(dB)**			
	1τ Delay	2τ Delay	3τ Delay	4τ Delay
Photonic crystal switch(τ=0.5ps)	1.22	2.22	1.02	0.78
MQW switch(τ=100ps)	1.08	1.98	0.73	0.53
Electro-optic switch	1.91	1.41	2.86	0.10

4.2 The switching characteristics of 3 different types of WSS with proper delay times for 40 Gbps/λ data rate

In this system, all 4 wavelengths are transmitted the signal with the 40 Gbps data rate per wavelength to 10 ONUs The 4 wavelengths are generated by the source of continuous wave (CW) laser array. The electrical signal is generated by the Pseudo-random bit sequence generator (PRBS) randomly. The randomness signals are sent to the NRZ pulse generator and then modulated by two Mach-Zehnder modulator as a NRZ-DQPSK transmitter with a data rate of 40 Gbps per wavelength. After that, all of them are combined in a multiplexer with an insertion loss of 1.5 dB. The differential group delay for polarization mode dispersion (PMD) value is 0.2 ps/km. After passing through the signal along the fiber, the signals are separated by demultiplexer with insertion loss value of 1.5 dB to the wavelength selective switches. After switching the signal by WSSs, it goes through the multiplexer again to merge the signal before sending it to the receiver. Each wavelength is adjusted to the value of the attenuation coefficient with optical attenuator and it was detected by two PIN photodetectors to receive the demodulated NRZ-DQPSK signal with the parameters of 0.9 A/W receiver responsivity, 10 nA of receiver dark current and 18.1381 x 10^{-12} A/Hz^0.5 of thermal noise. And then the low frequency electrical signals are filtered out by low-pass filter circuit with cutoff frequency of (0.75 x bit rate) [Hz].

The following are the results of the relation between received optical power(P_R) and log(BER) for 3 several different types of WSS with proper delay time(t_D=nτ,n=0,1,2,3,4). The performance of the system is evaluated in term of received optical power(P_R) for this worst case under the limitation of BER=10^{-4} (with FEC).

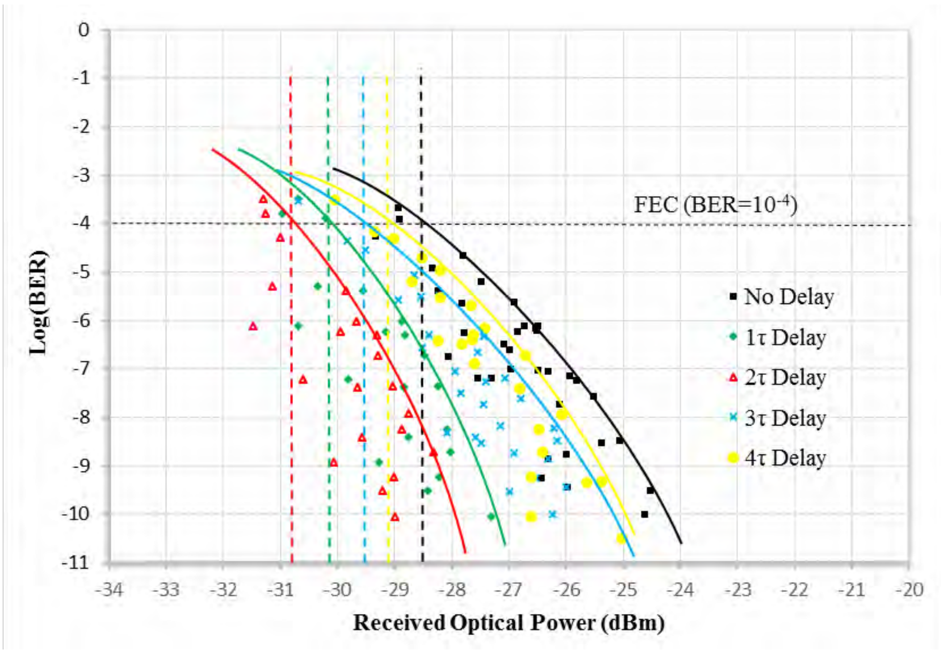


Figure 4-5 The relation between received optical power and Log(BER) for the 40Gbps/λ system using photonic crystal switch(τ = 0.5 ps) with the proper delay times(nτ, n = 0,1,2,3,4).

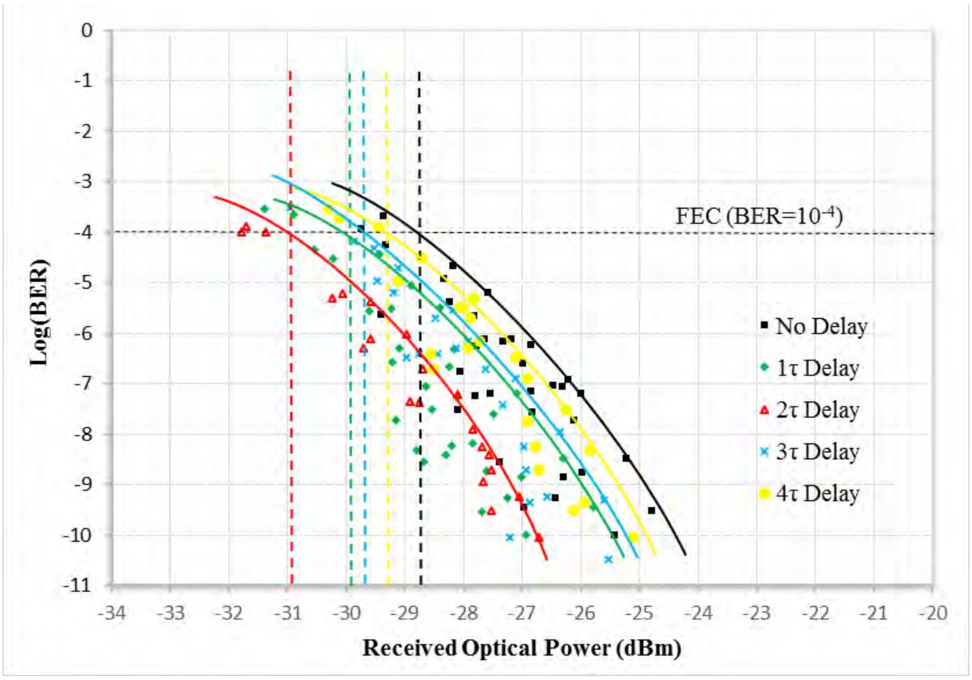


Figure 4-6 The relation between received optical power and Log(BER) for the 40Gbps/λ system using MQW switch(τ = 100 ps) with the proper delay times($n\tau$, n = 0,1,2,3,4).

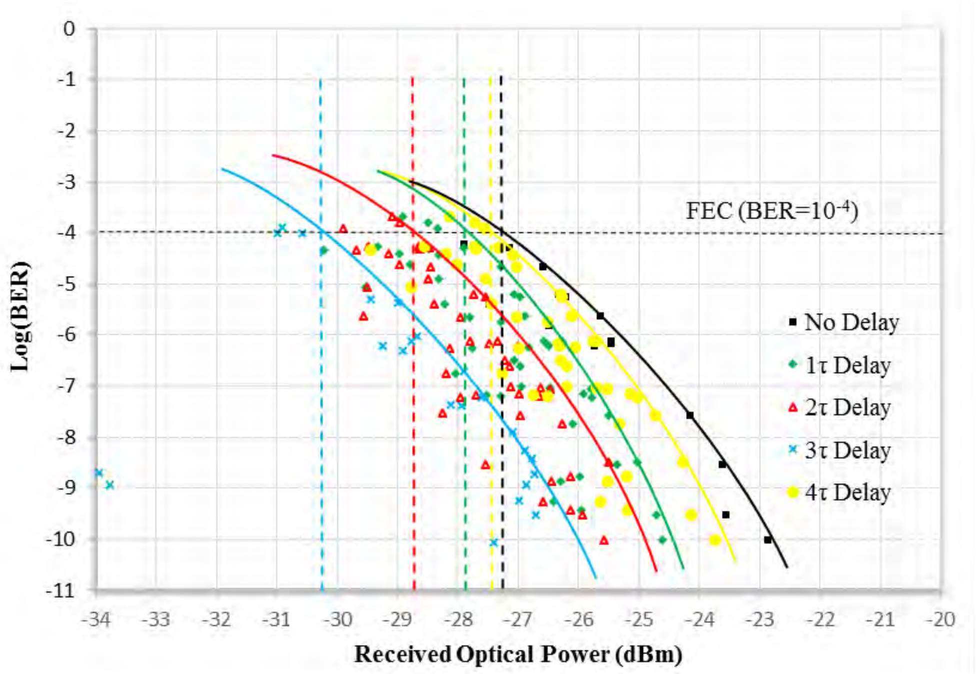


Figure 4-7 The relation between received optical power and Log(BER) for the 40Gbps/λ system using electro-optic switch(τ = 5 ns) with the proper delay times($n\tau$, n = 0,1,2,3,4).

Figure 4.4 - 4.6 show the relation between log(BER) and received optical power(P_R) by using the photonic crystal switch, the MQW switch and the electro-optic switch with the proper delay times(t_{D}=nτ,n=0,1,2,3,4) respectively. As the simulation results, the P_R for the system by using photonic crystal switch without delay time is -28.51 dBm and the others are -30.12 dBm, -30.81 dBm, -29.45 dBm and -29.13 dBm for using 1τ, 2τ, 3τ, 4τ delay time. And then, for the MQW switch, the P_R for the system by using without delay time is -28.67 dBm and -29.86 dBm, -30.95 dBm, -29.71 dBm,-29.31 dBm are the others P_R for using 1τ, 2τ, 3τ, 4τ delay time. As the last, for the electro-optic switch, the received optical power for the system by using electro-optic switch without delay time is -28.67 dBm and -29.86 dBm, -30.95 dBm, -29.71 dBm,-29.31 dBm are the others P_R for using 1τ, 2τ, 3τ, 4τ delay time. To sum up, for the photonic crystal switch and the MQW switch without delay time, the simulation results show the P_R for both switches are almost the same which are -28.51 dBm and -28.67 dBm respectively. When we applied 2τ delay time for these two switches, the system P_R can be achieved by the improvement of -30.85 dBm and -30.95 dBm respectively of course the power budgets can be improved with 2.34 dB and 2.28 dB respectively. On the other hand, the electro-optic switch without delay time system has P_R = -27.32 dBm and after using 3τ delay time, P_R is increased to -30.28 dBm that means the power budget is improved about 3dB (2.96 dB). Table 4.2 summarizes all of the received optical power for the system by using 3 different types of WSS with proper delay times.

Table 4.3 P_R of the 40Gbps/λ system by using proper delay times for 3 different types of WSS

Types of WSS	**Received Optical Power(P_R) at BER=10^{-4}(with FEC)**				
	No Delay	1τ Delay	2τ Delay	3τ Delay	4τ Delay
Photonic crystal switch(τ=0.5ps)	-28.51 dBm	-30.12 dBm	-30.81 dBm	-29.45 dBm	-29.13 dBm
MQW switch(τ=100ps)	-28.67 dBm	-29.86 dBm	-30.95 dBm	-29.71 dBm	-29.31 dBm
Electro-optic switch	-27.32 dBm	-27.85 dBm	-28.73 dBm	-30.28 dBm	-27.42 dBm

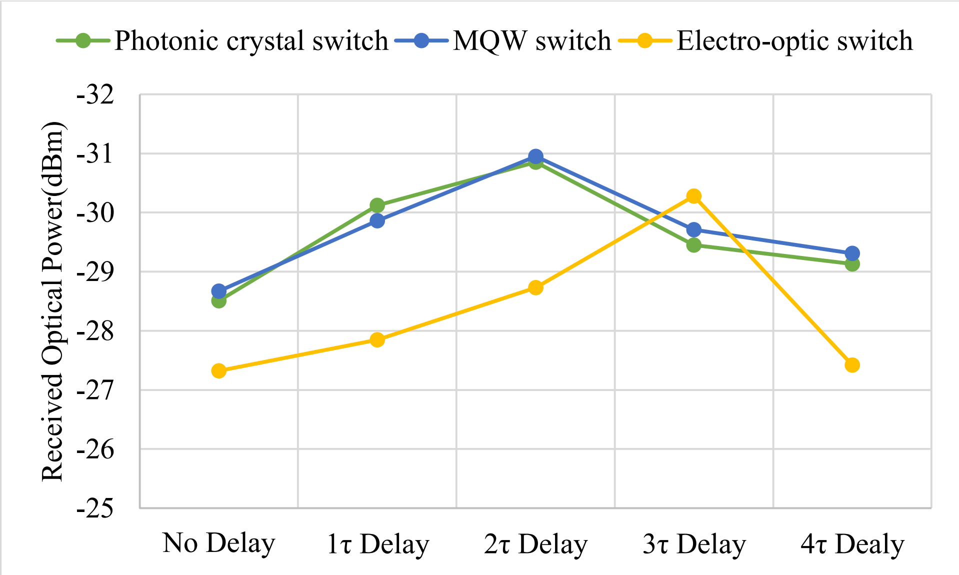


Figure 4-8 The relation between P_R and the proper delay times($n\tau$, n = 0,1,2,3,4) for 40Gbps/λ system

The variation of P_R after using 3 different WSSs without delay time and with 1τ, 2τ, 3τ, 4τ delay time is shown in Figure 7. As the results, the power budget is improved and we can clearly see that at most the power budget improvement is occurred in using 2τ delay time of photonic crystal switch and MQW switch. On the other hand, the power budget is improved at 3τ delay time for electro-optic switch.

Table 4.4 The system power budget improvement using 3 different types of WSS applied with proper delay times($n\tau$, n = 1,2,3,4)

Types of WSS	**Power Budget improvement(dB)**			
	1τ Delay	2τ Delay	3τ Delay	4τ Delay
Photonic crystal switch(τ=0.5ps)	1.61	2.34	0.94	0.62
MQW switch(τ=100ps)	1.19	2.28	1.04	0.64
Electro-optic switch	0.53	1.41	2.96	2.10

CHAPTER 5
DISCUSSION AND CONCLUSION

In this dissertation, we proposed the flexible FTTx system incorporated with DWBA to control the wavelength assignment on active WSSs which are replaced on the passive optical splitter in traditional PON. Due to short distance transmission, the signal is transmitted via ITU-T G652.D SMF counted on fiber attenuation and dispersion parameters without considering non-linear effect. In order to improve the system performance, we consider about the switching characteristics of WSS and focus on the signal distortion reduction by using 3 different types of WSS with the proper delay times($n\tau$, n = 0,1,2,3,4).

The results reveal that the providing of delay times significantly effects on the received optical power (P_R) and power budget improvement to reduce the signal distortion. The power budget improvement is outperformed at 2τ delay time of photonic crystal switch and MQW switch. On the other hand, the power budget is improved at 3τ delay time for the electro-optic switch about 3 dB.

For my opinion, without analytical approach, the BER will be taken directly from the simulation eye diagram by designing the control circuit for switching characteristics of WSS not to be randomly sequences. Moreover, the investigation of optimal delay time combining with mathematical model instead of the proper delay times, the results will be more accurate.

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APPENDIX

Simulation Model for Flexible FTTx by using WSSs incorporated with DWBA

This appendix will be illustrated the FTTx simulation model by using WSSs incorporated with DWBA controller on commercial computer simulation program Optisystem software version 10.0 related with the parameters of devices used to simulate for 4 wavelength to 10 ONUs at data rate of 10 Gbps/λ and 40 Gbps/λ system designs. There are main parameters of the system Also known as the global parameter, the OLT, the SMF ITU-T G.652.D optical fiber used in this system, active WSS switching characteristics using MATLAB programming to connect with Optisystem and the ONU, low-pass-filter, analyzer of BER detection at receiver section.

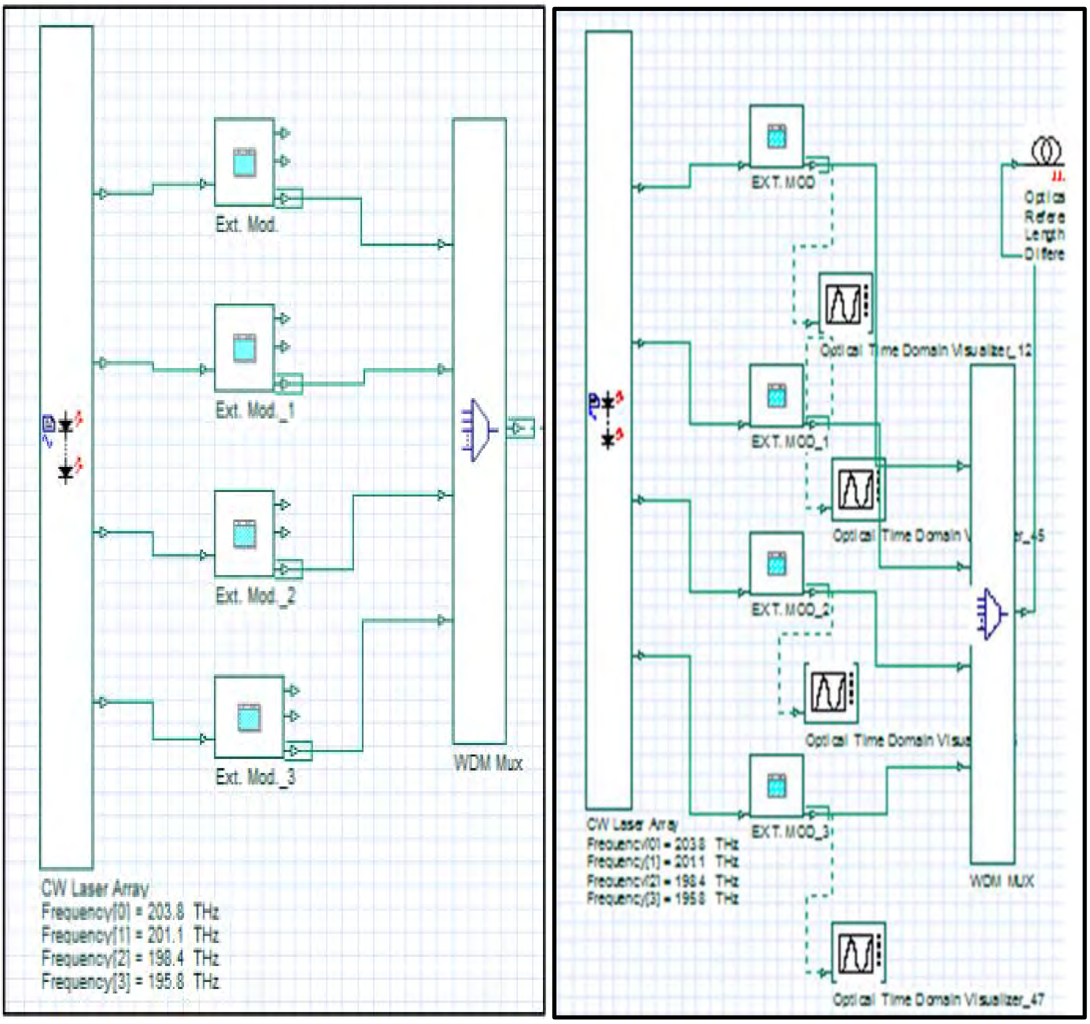
Global Parameter

Every the simulation of system should be set the global parameter of the system first such as the bit rate and the number of bits used for the transmission. A sample of a bit is used to generate for the FTTx by using WSS incorporated with DWBA. The setting of global parameter is as shown in Figure A-4 with a bit rate of 10 Gbps. 2048 bits and the number of samples per bit is 64 respectively.

OLT

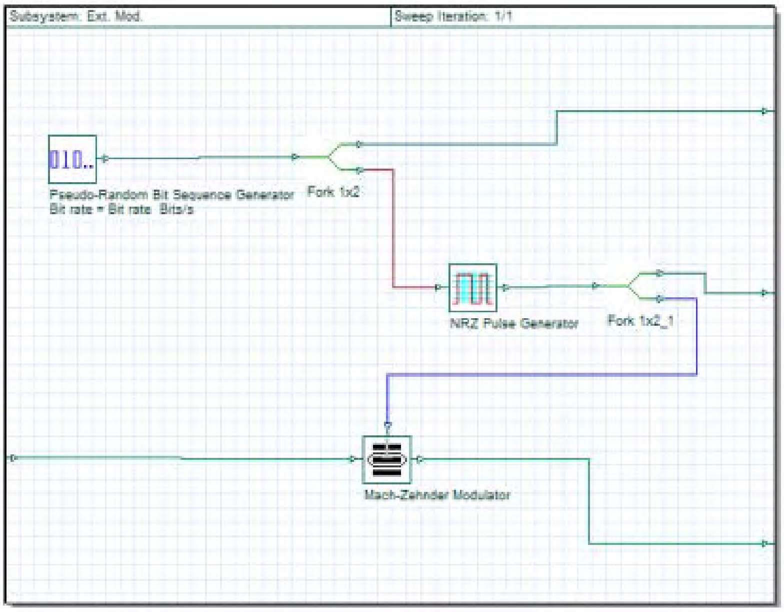
The OLT part consists of a CWDM array of continuous-wave (CW) laser, the external modulators and WDM multiplexers. For 4 wavelengths-10 ONUs system for both data rates are shown in Figure A-1(a) and (b). CW lasers generate the 4 CWDM wavelengths 1471, 1491, 1511 and 1531 nm. This simulation setting will be used in the following related frequency formats: 203.8, 201.1, 198.4 and 195.8 THz, respectively.

The external modulator models are as shown in Figure A-2 for (a) 10 Gbps/λ (NRZ-OOK modulation) and (b) 40Gbps/λ (NRZ-DQPSK modulation). Ext. Mod consists of a pseudo-random bit sequence generator generates a random. The bit rate is equal to the system bit rate of 10 Gbps and 40 Gbps. The signal is modulated by NRZ-OOK for 10 Gbps/λ and NRZ-DQPSK for 40 Gbps/λ finally the signal is modified by Mach-Zehnder modulators. All modulated signals are combined into a WDM multiplexer with the insertion loss of 1.5 dB.

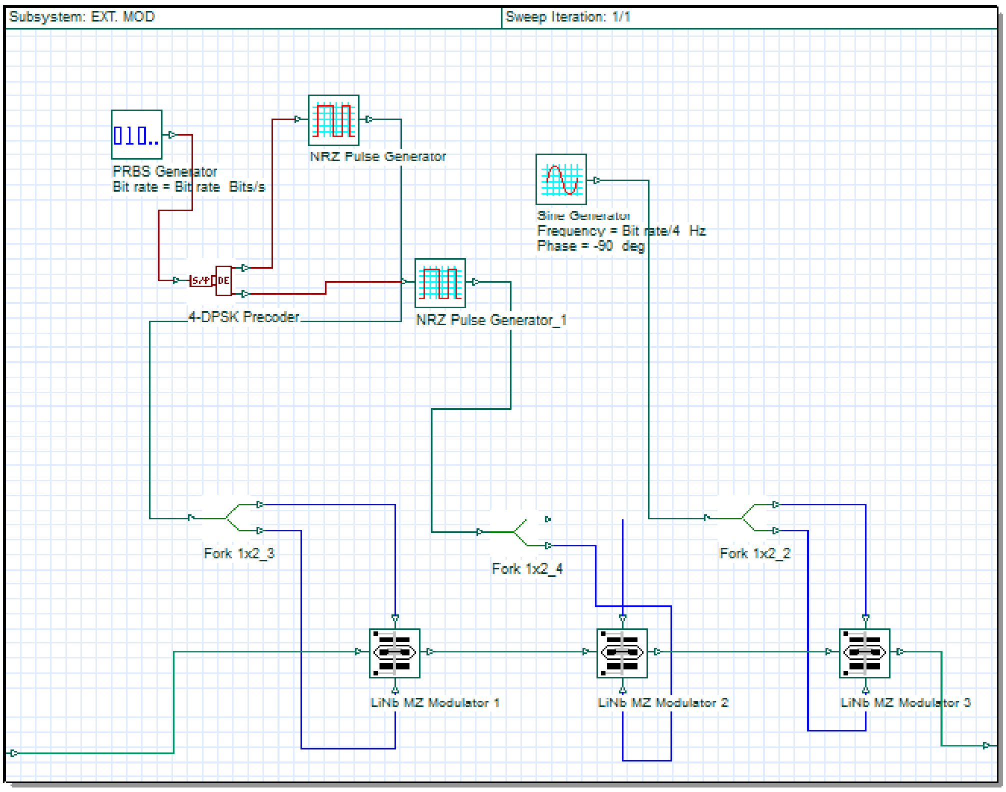


(a) (b)

Figure A-1 The OLT section of 4 wavelengths to 10 ONUs FTTx transmission system by using WSSs incorporated with DWBA for (a) 10 Gbps/λ and (b) 40Gbps/λ



(a)



(b)

Figure A-2 External Modulation section in OLT for (a) 10 Gbps/λ (NRZ-OOK modulation) and (b) 40Gbps/λ (NRZ-DQPSK modulation)

Optical Fiber

All wavelengths are combined with a WDM multiplexer with the insertion loss of 1.5 dB will be transmitted through the SMF ITU-T G.652.D optical fiber. The important parameters as the limiting system performance are attenuation and fiber dispersion. Both parameters are depends on the wavelengths of the system and shown in Table 2.4 for both data rates. PMD is 0.2 ps / km and the length of fiber is limited by 20 km because we will only focus on data rate and the performance of the signal will vary with the length of the fiber. After all the signal passes through the fiber, the signal then separated by WSSs for each wavelengths. The insertion loss of demultiplexer is also 1.5 dB.

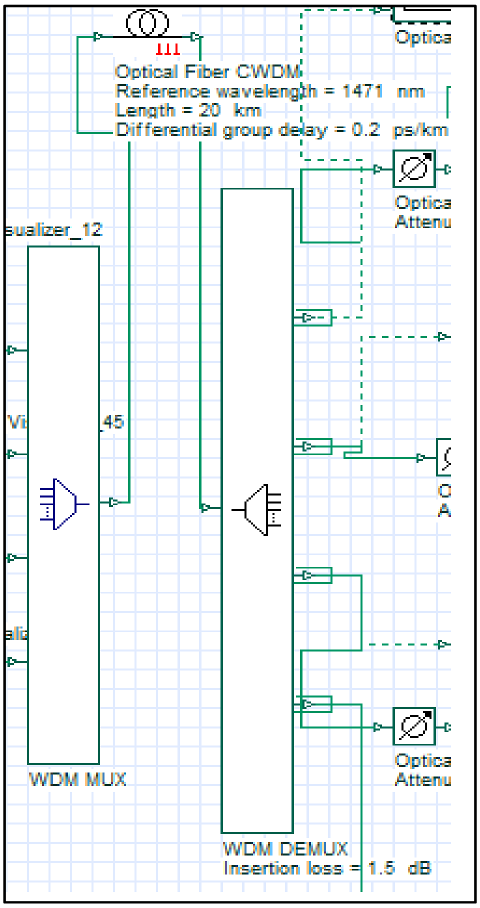


Figure A-3 Modeling of optical fiber at maximum reach 20 km for both data rates

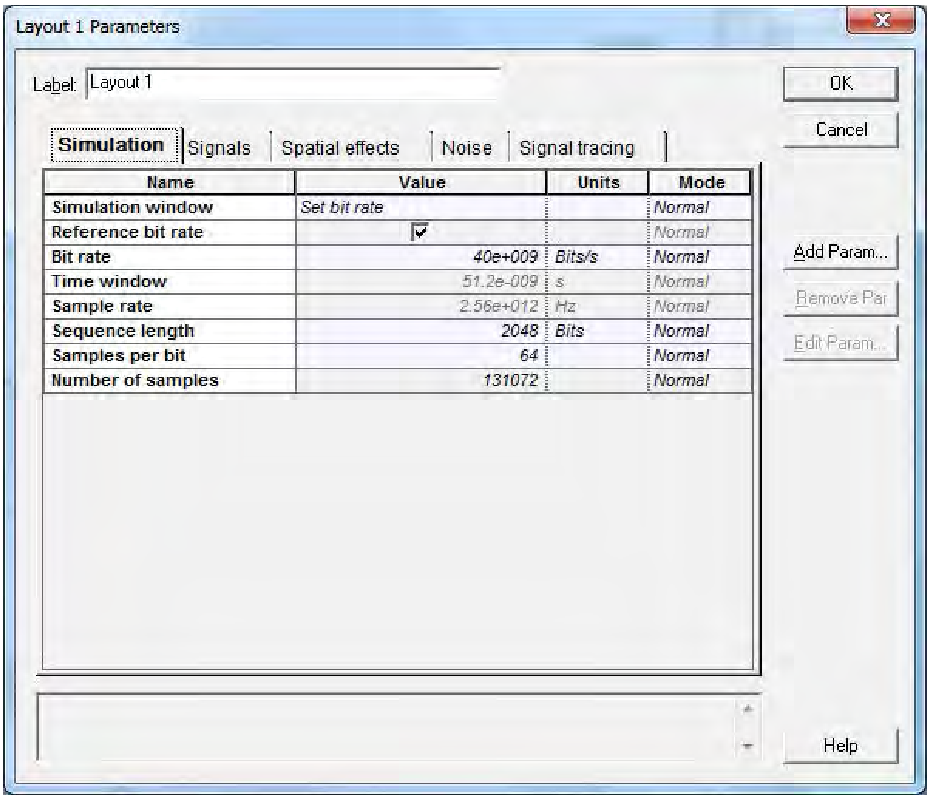


Figure A-4 Global parameters setting for 40 Gbps/λ

WSS

After passing the signal via the optical fiber and separated each signal wavelengths by demultiplexers. CWDM wavelengths will be allocated by the WSS to each ONUs as request. The WSS using in this system is created by a MATLAB program and linked with the Optisystem.

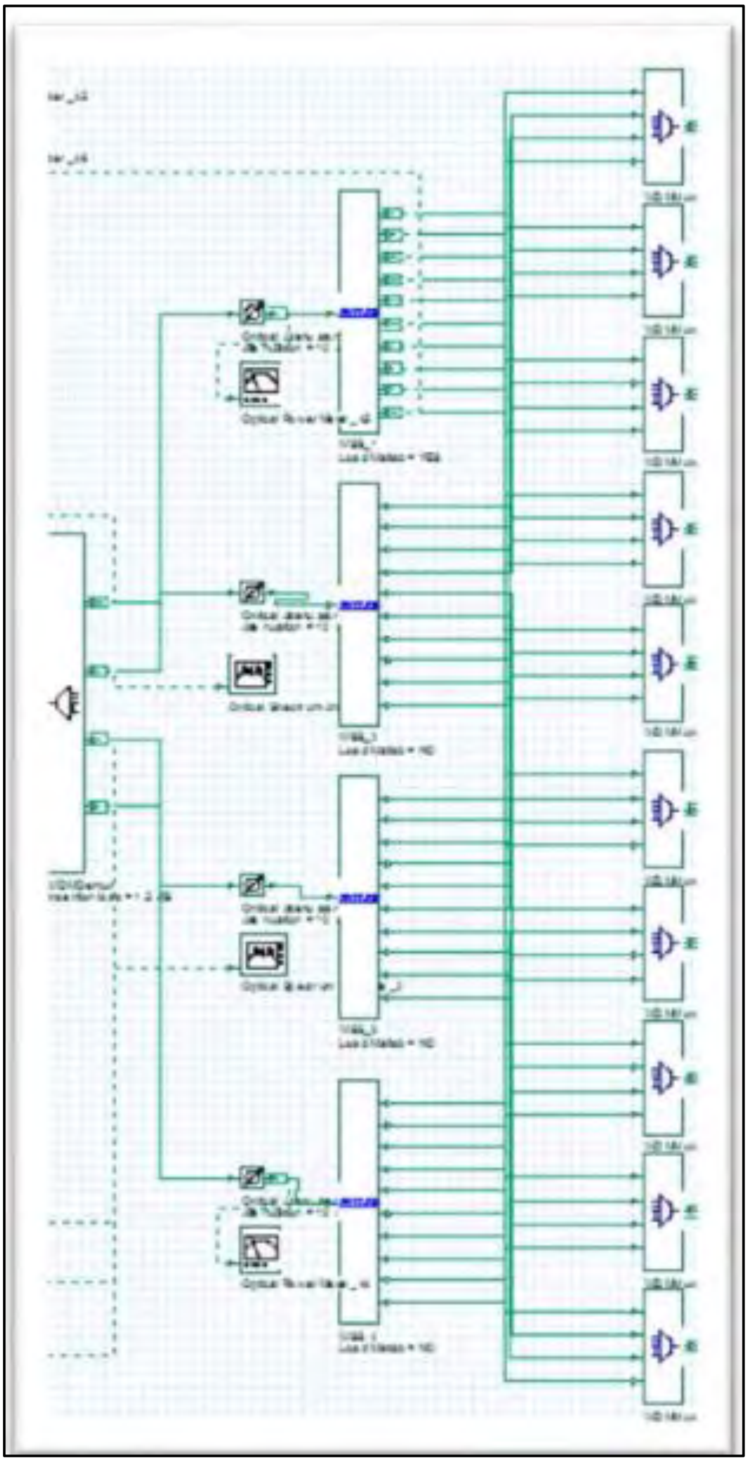


Figure A-5 WSSs modelling for both data rates

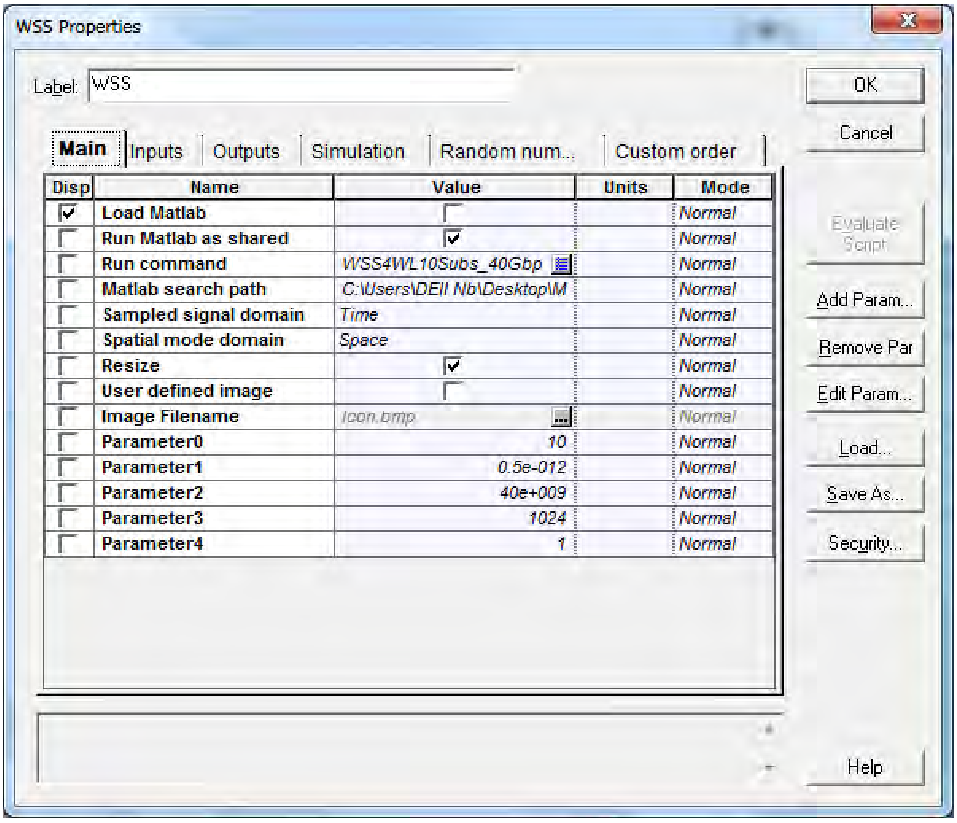


Figure A-6 The main and user parameters setting of WSS

```
OutputPort1 = InputPort1;
OutputPort2 = InputPort1;
OutputPort3 = InputPort1;
OutputPort4 = InputPort1;
OutputPort5 = InputPort1;
OutputPort6 = InputPort1;
OutputPort7 = InputPort1;
OutputPort8 = InputPort1;
OutputPort9 = InputPort1;
OutputPort10 = InputPort1;

m = Parameter0; %no. of switching
T = Parameter1; %time constant of switch
datarate = Parameter2;%data rate
bitnum = Parameter3; %sequence length
SwitchNo = Parameter4;%switch number
home=10;

MaxSwitchNo = length(InputPort1.Sampled);
OptdataIn = InputPort1.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal;
SampleNumber = length(OptdataIn);
```

Figure A-7 MATLAB code for declaring variables

```
A1=sort(randi(SampleNumber,[1,m*2]),2); % a vector of 2m elements, the element values are random integers
SampledTime = ((1/datarate)*bitnum)/SampleNumber;
DelayTime = (T/SampledTime)*(2);  %T=Parameter1, Delay time 0T,1T,2T,3T,4T
for i=1:1;home; %assigning all switching characteristics of all homes be zeros.
Htemp2(i)=1;
   for n=1:1:SampledNumber;
       t(n)=SampledTime*n;
       H(i,n)=0;
       end
end
for x=1:2:2*m % start loop of switching
    q=randi(home); %random home for receiving signal

    if (x ~= 1)
        if (A1(1,x) < A1(1,x-1)+DelayTime)%check the condition of overlapping
            A1(1,x)=A1(1,x-1)+DelayTime; %shifting rising edge
            A1(1,x+1)=A1(1,x+1)+DelayTime; %shifting falling edge
        end
    else
        A1(1,x)=A1(1,x);
    end
```

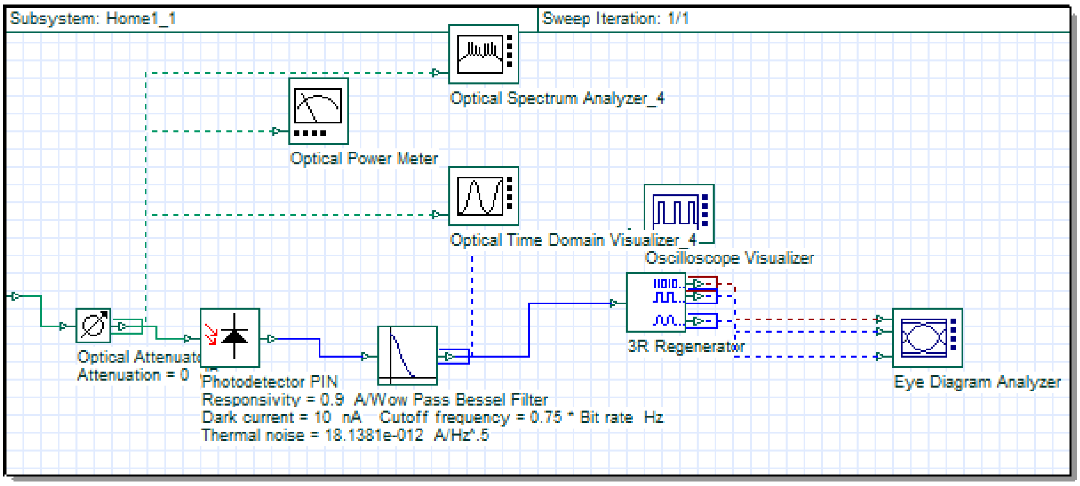
Figure A-8 Adding delay times and in WSS switching characteristics

```
    %rising time
    for n=A1(1,x)+1:1:A1(1,x+1)
            Htemp1(q,n)=Htemp2(q)*(1-exp(-(t(n)-(A1(1,x))*SampledTime)/T));
            H(q,n)=H(q,n)+Htemp1(q,n);
    end
    Htemp2(q)=H(q,A1(1,x+1));

    % falling time
    for n=A1(1,x+1)+1:1:SampleNumber
        Htemp1(q,n)=Htemp2(q)*exp(-(t(n)-(A1(1,x+1))*SampledTime)/T);
        H(q,n)=H(q,n)+Htemp1(q,n);
    end
end
```

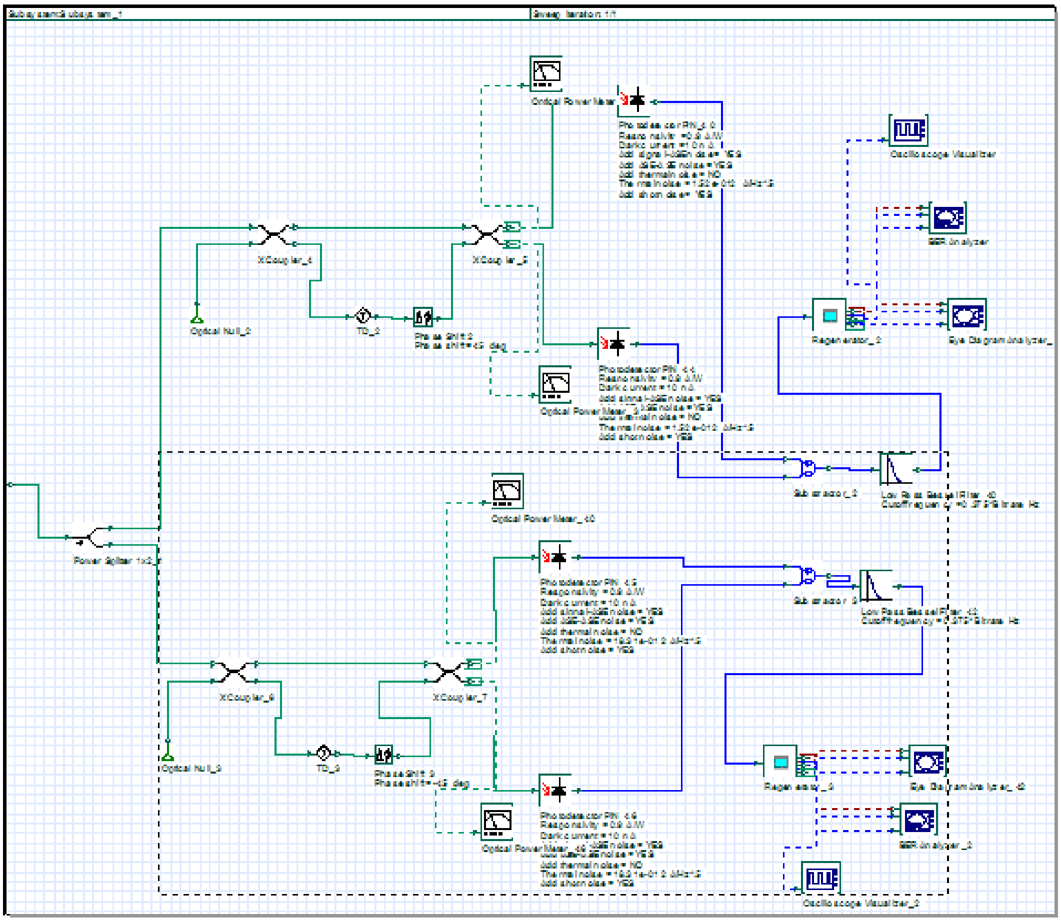
Figure A-9 WSS switching configuration

```
OptdataOut1 = (sqrt(H(1,:))./sqrt(2)).*OptdataIn;
OptdataOut2 = (sqrt(H(2,:))./sqrt(2)).*OptdataIn;
OptdataOut3 = (sqrt(H(3,:))./sqrt(2)).*OptdataIn;
OptdataOut4 = (sqrt(H(4,:))./sqrt(2)).*OptdataIn;
OptdataOut5 = (sqrt(H(5,:))./sqrt(2)).*OptdataIn;
OptdataOut6 = (sqrt(H(6,:))./sqrt(2)).*OptdataIn;
OptdataOut7 = (sqrt(H(7,:))./sqrt(2)).*OptdataIn;
OptdataOut8 = (sqrt(H(8,:))./sqrt(2)).*OptdataIn;
OptdataOut9 = (sqrt(H(9,:))./sqrt(2)).*OptdataIn;
OptdataOut10 = (sqrt(H(10,:))./sqrt(2)).*OptdataIn;

OutputPort1.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut1;
OutputPort2.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut2;
OutputPort3.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut3;
OutputPort4.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut4;
OutputPort5.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut5;
OutputPort6.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut6;
OutputPort7.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut7;
OutputPort8.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut8;
OutputPort9.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut9;
OutputPort10.Sampled(1,MaxSwitchNo-SwitchNo+1).Signal = OptdataOut10;
```

Figure A-10 Connecting ports of Optisystem and MATLAB code



(a)



(b)

Figure A-11 ONU model for (a) 10Gbps/λ(NRZ-OOK) and (b) 40Gbps/λ(NRZ-DQPSK receiver)

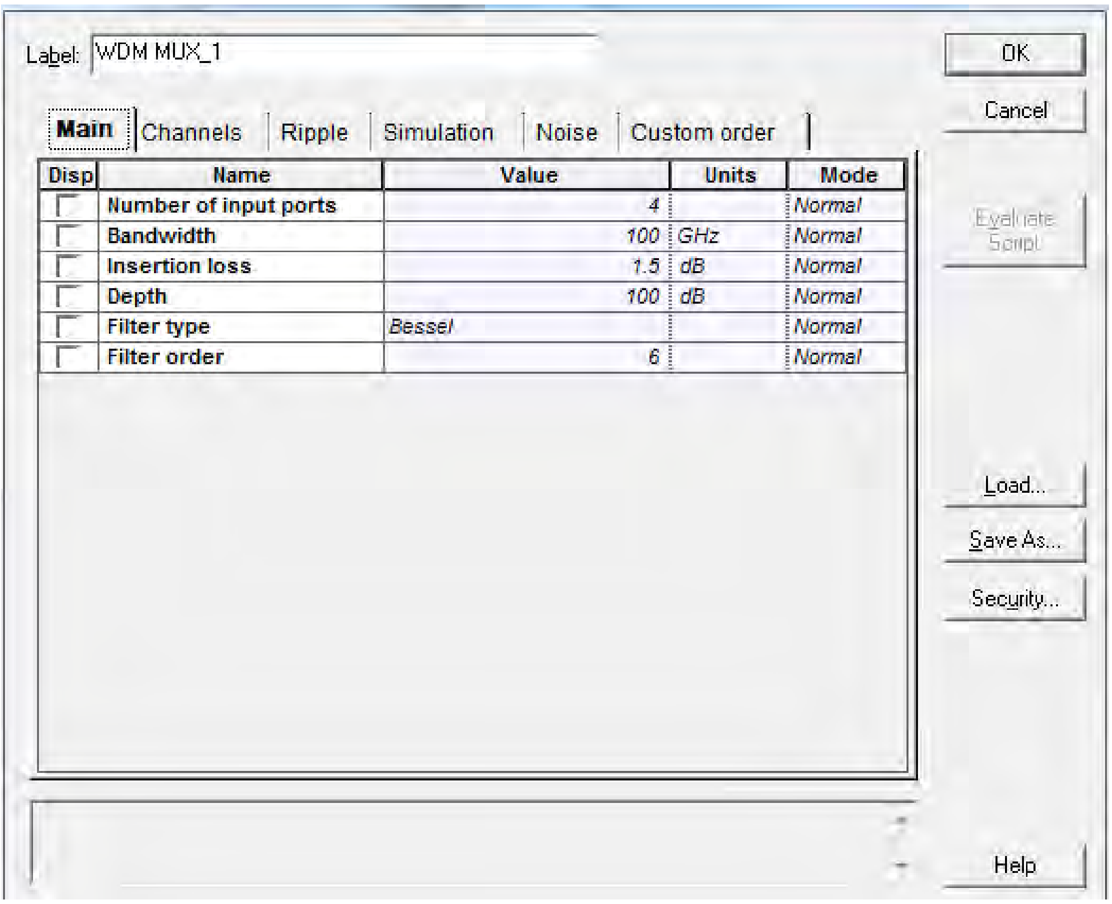


Figure A-12 WDM setting for the 10 Gbps/λ

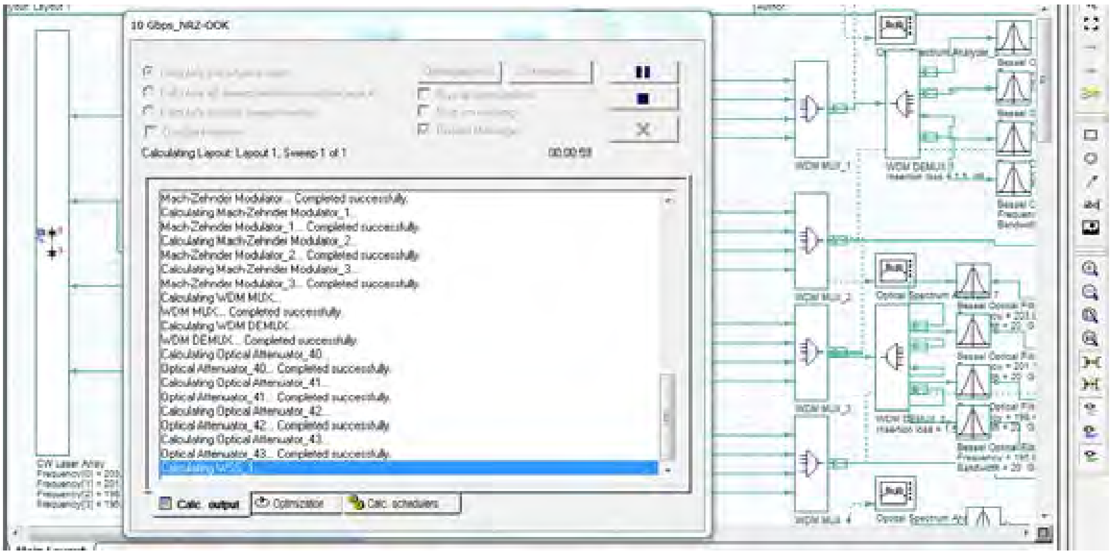


Figure A-13 Simulating the system for the results

ONU

The receiver section mainly consists of an optical attenuator, PIN photo detector and low pass filter. The wavelength is adjusted to 3 dB attenuation and the signal is detected with a PIN photodetector. It can receive 90% of 0.9 A/W receiver responsivity, the receiver dark current is 10 nA and thermal noise value is 18.1381 x 10^{-12} A/Hz^0. After that, the low frequency electrical signals are filtered out by low-pass filter circuit with cutoff frequency of (0.75 x bit rate) [Hz]. The receiver models of both data rates system are shown in Figure A-11 (a) and (b).

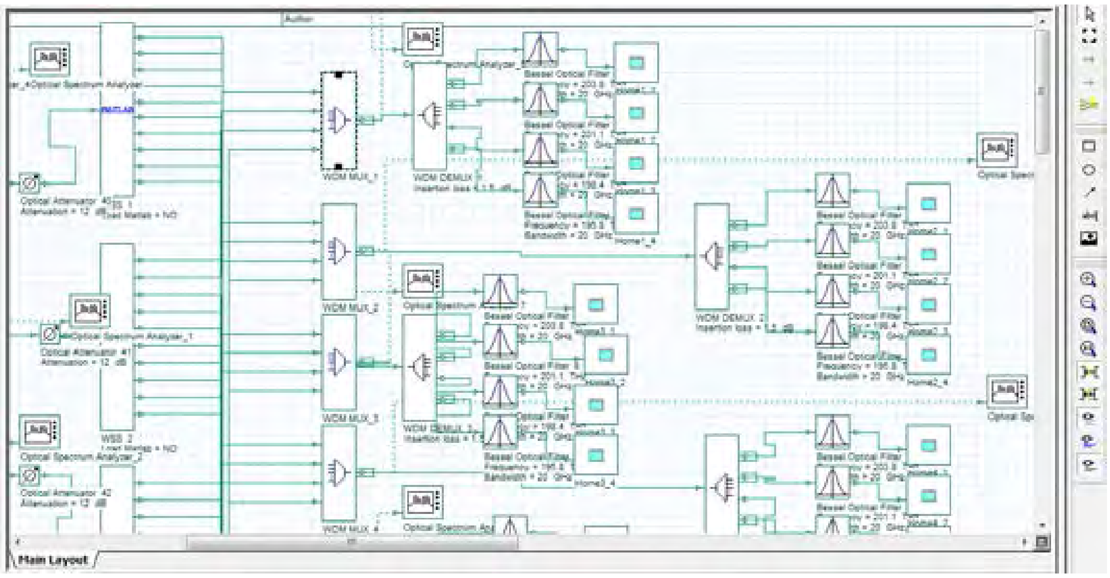


Figure A-14 ONU design at the receiver section

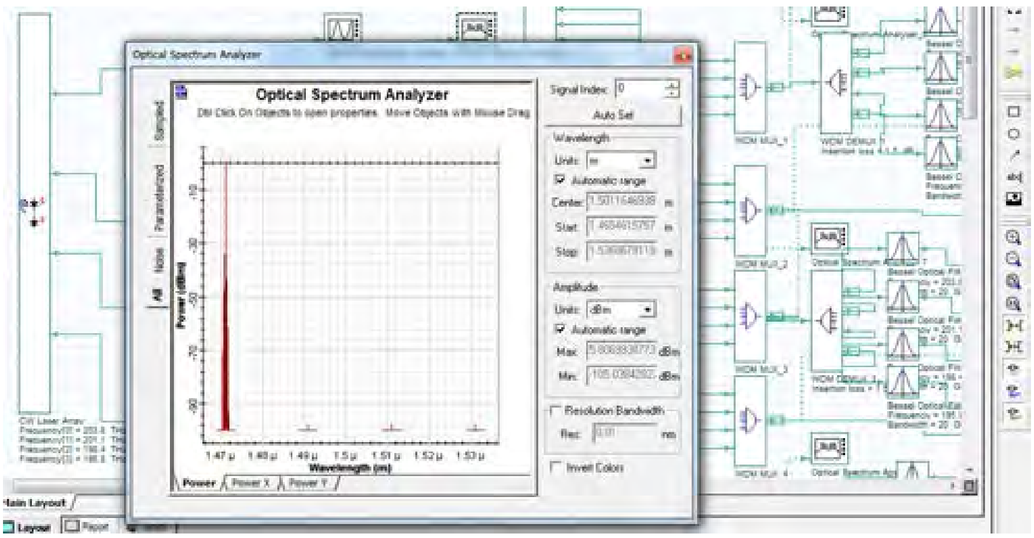


Figure A-15 Measurement of the optical signal after passing through the fiber

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	(2) A Complete Guideline to Design a Flexible Fiber Access Network using Active Wavelength Selective Switches. IEEE Access Journal(Waiting for decision)