UNIVERSITI PUTRA MALAYSIA

PERFORMANCE EVALUATION OF NEXT GENERATION PASSIVE OPTICAL NETWORKS STAGE TWO FOR DOWNSTREAM TRANSMISSION

RAWA MUAYAD MAHMOOD

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PERFORMANCE EVALUATION OF NEXT GENERATION PASSIVE OPTICAL NETWORKS STAGE TWO FOR DOWNSTREAM TRANSMISSION

By

RAWA MUAYAD MAHMOOD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillments of the Requirements for the Degree of Master of Science

October 2017

DEDICATION

To my:
Beloved parents,
Sisters and brothers,
Beloved husband, Ibrahim, and
Daughters, Malk, Lara and Lamar

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

PERFORMANCE EVALUATION OF NEXT GENERATION PASSIVE OPTICAL NETWORKS STAGE TWO FOR DOWNSTREAM TRANSMISSION

By

RAWA MUAYAD MAHMOOD

October 2017

Chairman : Siti Barirah Ahmad Anas, PhD
Faculty : Engineering

In this work, a 40 Gb/s downstream time and wavelength division multiplexing-passive optical network (TWDM-PON) for next-generation passive-optical-network second stage (NG-PON2) had been designed and demonstrated using VPI simulator. This work establishes simulation, analysis and performance evaluation of three different wavelength plans in TWDM-PON. TWDN-PON is selected as a primary solution to NG-PON2 in order to achieve and support the 40Gbit/s bandwidth requirement. A four 10-Gb/s TWDM-PON signals are stacked using four different wavelengths in the downstream direction and externally modulated.

The three different wavelength plans have been simulated and evaluated so that the best plan can be selected in order to study the effect of distances and number of users. The downstream wavelengths for plan 1 and 3 range from 190.2 THz to 189.6 THz while for plan 2 the wavelengths range from 192.9 THz to 192.6 THz.

Distance of 80 km and 100 km length with an optimum attenuation of 0.2 dB /km was employed to transfer the multiplexed signal. Based on the simulation results, the enhanced prototype system is able to support split ratio of 1:256 and 1:512.

It can be concluded that for downstream transmission over 80 km and 100 km single mode fiber (SMF), plan 2 performs better than plan 1 and 3. Thus, plan 2 is further analyzed for transmission of triple play services which consist of voice, video and data.

The system performance is observed using Bit Error Rate (BER) and Optical Signal-to-Noise Ratio (OSNR) with respect to the design parameters such as distance, number of users and received optical power. Thus, two different systems were implemented in term of number of supportable users, which are 256 users and 512 users, as well as the transmission distance that are 80 km and 100 km. When the system is tested upon transmission of triple-play services over 80km distance with 512 users, it is shown that BER of 8.9×10^{-10}, 3.9×10^{-9} and 1.3×10^{-4} are achieved for data, voice and video, respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENILAIAN PRESTASI BAGI GENERASI BARU JARINGAN OPTIK PASIF PERINGKAT KEDUA UNTUK PENGHANTARAN HILIRAN

Oleh

RAWA MUAYAD MAHMOOD

Oktober 2017

Pengerusi : Siti Barirah Ahmad Anas, PhD
Fakulti : Kejuruteraan

Dalam kerja ini, sebuah 40 Gb/s hiliran pemultipleksan pembahagian masa dan panjang gelombang - rangkaian optik pasif (TWDM-PON) untuk generasi baru bagi rangkaian optik pasif peringkat kedua (NG-PON 2) telah direka bentuk dan ditunjukkan melalui penggunaan VPI simulator. Kerja ini menetapkan simulasi, analisis dan penilaian prestasi bagi perbandingan antara tiga pelan panjang gelombang yang berbeza dalam TWDM-PON. TWDN-PON dipilih sebagai penyelesaian utama untuk NG-PON2 untuk mencapai dan menyokong keperluan jalur lebar 40Gbit/s. Empat isyarat 10 Gb/s TWDM-PON disusun menggunakan empat panjang gelombang yang berbeza ke arah hilir dan dimodulasi secara luaran.

Ketiga-tiga pelan panjang gelombang disimulasi dan dinilai supaya pelan yang terbaik boleh dipilih untuk mengkaji kesan jarak dan bilangan pengguna. Panjang gelombang hiliran daripada pelan 1 dan 3 adalah berbeza-beza, dari 190.2 THz kepada 189.6 THz manakala bagi pelan 2 panjang gelombang antara 192.9 THz kepada 192.6 THz.

Jarak 80 km dan 100 km dengan pengecilan optimum sebanyak 0.2 dB/km telah digunakan untuk memindahkan isyarat multipleks. Berdasarkan keputusan simulasi, sistem prototaip yang telah dipertingkatkan mampu untuk menyokong nisbah pecahan sebanyak 1: 256 dan 1: 512.

Dapat disimpulkan bahawa untuk penghantaran hiliran lebih 80 km dan 100 km gentian satu mod (SMF) dalam pelan 2 lebih baik daripada pelan 1 dan 3. Oleh itu, pelan 2 seterusnya dianalisis untuk penghantaran perkhidmatan tiga serangkai yang terdiri daripada suara, video dan data.

Prestasi sistem diperhatikan dengan menggunapakai kadar ralat bit (BER) dan nisbah isyarat kepada hingar optik (OSNR) berkenaan dengan parameter reka bentuk seperti jarak, bilangan pengguna dan kuasa optic yang diterima. Oleh itu, dua sistem yang berbeza telah dilaksanakan dari segi bilangan pengguna yang dapat disokong, iaitu 256 dan 512 pengguna, dan juga jarak penghantaran iaitu 80 km dan 100 km. Apabila sistem ini diuji untuk tiga penyampaian perkhidmatan dengan jarak 80km dan jumlah pengguna adalah sebanyak 512, nilai BER yg ditunjukkan untuk data, suara dan video masing-masing adalah $8.9x10^{-10}$, $3.9x10^{-9}$ dan $1.3x10^{-4}$.

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Last but not least, I am proud and grateful of my beloved mother and father which their support and patience was my ever encouragement in this endeavor, I would like to thank the rest of my family, sisters and brothers who keep encouraging and supporting me in whatever I do. Thank you very much.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

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This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

AON	Active Optical Network
ASE	Amplification Spontaneous Emission
ATM PON	Asynchronous Transfer Mode Passive Optical Network
BER	Bit Error Rate
BPON	Broadband PON
C-band	Conventional band
CD	Chromatic Dispersion
CE	Coexisting Element
CO	Central Office
CW	Continuous-Wave
DBA	Dynamic Bandwidth Allocation
DFB	Tunable Distributed Feedback Lasers
DI	Delay Interferometer
DML	Directly Modulated Lasers
DPSK	Differential Phase Shift Keying
DSL	Digital Subscriber Loop
DWDM	Dense WDM
E-band	Extended band
EDFAs	Erbium-Doped Fiber Amplifiers
EPON	Ethernet Passive Optical Network
EVM	Error-Vector Magnitude
FSAN	Full Service Access Network
FTTB	Fiber To The Business

FTTC	Fiber To The Curb
FTTH	Fiber-To-The-Home
FTTN	Fiber To The Node
FTTP	Fiber To The Premises
FTTx	Fiber-To-The-x
GEPON	Gigabit Ethernet Passive Optical Network
IEEE	Institute of Electrical and Electronics Engineers
ITU-T	International Telecommunication Union
L-band	Long minus band
MZM	Mach- Zehnder Modulator
NG-PON1	Next Generation-PON Stage 1
NG-PON2	Next Generation-PON Stage 2
NRZ	Non-Return to Zero
O-band	Original band
OCDM	Optical Code Division Multiplexing
ODN	Optical Distribution Network
OFDM-PON	Orthogonal Frequency Division Multiplexed PON
OLT	Optical Line Terminal
ONU	Optical Network Units
OOK	On-Off Keying
OPM	Optical Power Meter
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal-to-Noise Ratio
P2MP	Point-to-Multi Point
P2P	Point-to-Point

PIN	Positive Intrinsic Negative receiver
PMD	Physical Media Dependent
PON	Passive Optical Network
PRBS	Pseudo-Random Data Generator
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RF	Radio Frequency
RN	Remote Node
ROP	Received Optical Power
Rx_El-mQAM	Electrical M-QAM Receiver
RZ	Return Zero
SCM	Sub Carrier Multiplexing
SDH	Synchronous Digital Hierarchy
SER	Symbol Error Rate
SMF	Single Mode Fiber
TDM	Time-Division Multiplexing
TDM-PON	Time Division Multiplexing
TOF	Tunable Optical Filter
TWDM-PON	Time and Wavelength Division Multiplexing Passive Optical Network
Tx_El-mQAM	Electrical M-QAM Transmitter
UD-WDM	Ultra-Dense Wavelength Division Multiplexing
UNI	User Network Interfaces
VoIP	Voice over Internet Protocol
VPI	Virtual Photonics Inc.
WDM	Wavelength-Division Multiplexing

WDM/TDM-PON	Wavelength Division Multiplexing/Time Division Multiplexing PON
WDM-PON	Wavelength Division Multiplexing PON

CHAPTER 1

INTRODUCTION

1.1 Background

Over the past decade, there had been a rapid global growth in Internet usage with a corresponding increase in Internet traffic volume. With recent technological advances and insights, this trend is expected to develop in the future. Most daily routine activities encompass a repeated use of the bandwidth demanding applications. Thus, high capacity networks are required to support the enormous bandwidth requirements, due to the increased number of internet users for a new online application. The key technology to achieve high capacity network infrastructures, which are able to cope with this exponential increase in global traffic volume is optical fiber communication [1].

The increased usage of high bandwidth-demanding services such as Voice over Internet Protocol (VoIP), live video streaming as well as peer to peer passage of information led to a proportional increment in consumers' demand for bandwidth that has high-speed fiber connections, to the homes as well as premises. The demand of residential subscribers is first mile access solutions that offers high bandwidth and media rich services. Meanwhile, there is high demand for broadband infrastructure by corporate by which they can access their LAN to the internet backbone [2]. In order to meet this bandwidth demand, Fiber-To-The-x (FTTx) had emerged, delivering high speed ultra-fast broadband in order to achieve the requirement of next-generation multiplay service applications.

A lot of broadband access technologies are in existence nowadays, examples like copper based digital subscriber loop (DSL), wireless and fiber access. However, the fiber access is seen to be the feasible technology for the future access networks [3-5]. Fiber-to-the-home (FTTH) is the future proofing technology present ultra-high bandwidth and long reach transmission. Many network architectures have been developed, e.g., point-to-point (P2P), active optical network (AON) [6] and passive optical network (PON) [2, 7, 8]. Due to the low deployment cost and resource efficiency, PON is considered as the most promising solution. PON is further classified into three types on the basis of two different technologies which are time-division multiplexing (TDM) and wavelength-division multiplexing (WDM). The three types of PON which are based on this classification include TDM PON, WDM PON and hybrid WDM/TDM PON.

In supporting numerous services simultaneously, optical fiber networks are the most preferred due to its remarkably high bandwidths offer compared to conventional access technology such as twisted pair copper wires or coaxial cables. FTTH is a transfer of information signal over the optical fiber from the operator's switching equipment to the home or business premises. This method is relatively new, fast growing, and provides the highest bandwidth to end users, hence enabling more robust internet services [9].

The transmission allow the delivery of triple play services which are data, voice and video. FTTH-PON architectures can support an Ethernet connection over a specific PON protocol standard [10]. Currently, PON standards in use are Ethernet Passive Optical Network (EPON) or GE-PON.

PONs is now installed in a lot of countries so as to make provision for high-speed broadband services. During the early years in the gradual change in multiplexing technologies, an upstream and downstream aggregate bandwidth of 155 Mbit/s up to 622 Mbit/s was achieved with the use of Asynchronous Transfer Mode (ATM) PON (APON) and Broadband PON (BPON). However, the introduction of TDM later permitted the achievement of a downstream and upstream bandwidth of around 1.25 Gbit/s and 2.5 Gbit/s respectively, according to the International Telecommunication Union (ITU-T) G.984 GPON standard. In addition, improved high-speed TDM that is based on optical access systems up to 10Gbit/s for downstream and 2.5 Gbit/s upstream (XG-PON1) or 10 Gb/s for combined downstream and upstream (XG-PON2) have been developed in accordance with ITU-T G.987 GPON specification. Presently, standard specifications by ITU exist for APON and BPON, GPON, XG-PON , EPON and 10 GE-PON by Institute of Electrical and Electronics Engineers (IEEE). However, with the introduction of WDM in transport networks, a significant increase in capacities to a bandwidth of 250 GBit/s up to 500 Gbit/s using Ultra-Dense Wavelength Division Multiplexing (UD-WDM) have been consistently reported. The generation of optical access networks that operates at over 10-Gbit/s is now considered more flexible network architectures using WDM to respond to high bandwidth requests. Time and Wavelength Division Multiplexing Passive Optical Network (TWDM-PON) has emerged as a high potential PON solution by providing high capacity bandwidth to satisfy the demand for high-speed broadband services [11].

A new upgrade was suggested namely Next Generation-PON Stage 1 (NG-PON1), which support a data rate up to 10-Gb/s. Furthermore, Next Generation-PON Stage 2 (NG-PON2) as a further improvement to NG-PON1 is proposed by Full Service Access Network (FSAN) as a promising candidate for supporting 40-Gb/s data rate [12]. The researchers found a different techniques for NG-PON2 [13]. NG-PON2 includes WDM-PON, Orthogonal Frequency Division Multiplexed PON (OFDM-PON) and TWDM-PON. A single wavelength channel is shared by all the users at the Remote Node (RN) with the help of a splitter in TDM-PON. Multi-wavelength TDM-PON provides a better smooth capacity upgrade by combining multiple wavelengths on the existing TDM-PON which is known as TWDM-PON [12].

1.2 Motivation

There are many promising features which make TWDM-PON a popular technology for next generation [11, 14-17].

- From both technical and economic perspectives, the ability to provide potentially unlimited transmission capacity is the most obvious advantage of TWDM technology.
- Fast, simple, and dynamic provisioning of network connections give providers the ability to provide high-bandwidth services.
- PONs allow for long reach between the CO and customer premises, operating at long distances.
- PONs provide higher bandwidth due to deeper fiber penetration, offering Gb/s solutions.
- Operating in the downstream as a broadcast network, PONs allow for video broadcasting.
- TWDM-PON not complicated configuration and maintenance at the ODN.

A lot of setups have been investigated in TWDM-PON with consideration to the design shown in the standard and the presence of the optical devices. Using this case as beginning point, this work intends to evaluate the modern international standard for the FTTH networks implementing NG-PON2 systems that operates at 4 × 10GBit/s for three different wavelength plan options and comparing them in order to determine and evaluate their performance in terms of longer transmission distance and higher number of supportable users. The solution is designed and developed using Virtual Photonics Inc. (VPI) simulation software. Various tests are performed, and optimization of the system is done with the aid of VPI software.

This thesis is first study the fundamental concepts that distinguish TWDM from other techniques with emphasis on the comparison of three wavelength plan options in the downstream direction. The three plan options are simulated and evaluated in this thesis. The best plan is chosen and analyzed further in terms of the transmission distance and number of supportable users.

1.3 Problem statement

The explosive growth of online multimedia software like the VoIP, video conferencing as well as online-gaming has placed increasing demands on the ability and reliability of transmission systems. Optical networks such as PONs have emerged to address this problem by providing sufficient bandwidth for these applications [16, 18-20].

The three options proposed for the TWDM-PON wavelengths as described in ITU-T recommendations. The first choice is to reuse the XG-PON wavelength bands which is a finer grid inside NG-PON1 band. This option band can be combined with GPON and the loss budget is similar to that of XG-PON. The typical loss budget value is about 33 dB. The next choice to the initial option is to redefine the C-band enhancement band to include the upstream and downstream wavelengths. This option plan makes the system compatible with GPON and XG-PON, with help of EDFAs. The third option is like a hybrid, which combines features of the above two plans. The downstream channels of this plan are designed in the L-minus band, while the upstream channels are located in the C-minus band. This option plan is compatible with GPON and the RF video overlay channel, but blocks XG-PON. This three plan options are discussed further in the next chapter.

The three wavelength plans were chosen due to coexistence with the previous generations of PONs in the legacy Optical Distribution Network (ODN) such as XG-PON and GPON [16]. In addition to that, the three wavelength plans are proposed for the TWDM-PON system by ITU-T recommendations.

Many research works are done on the NG-PON2 architecture [11, 16, 20-22]. The research [20] showed a successful transmission of the proposed work through simulation study where an aggregate capacity of 40 Gb/s is transported over 40 km transmission distance with 32 splits. The study [16] summarized the TWDM-PON research in FSAN by reviewing the basics of TWDM-PON and presenting the world's first full-system 40 Gb/s TWDM-PON prototype. The research [21] proposed a two-phased upgrade method of capacity per wavelength in NG-PON2. Coexistence with conventional NG-PON2 ONUs and a higher capacity are realized using star 8-QAM and square 16-QAM in phases 1 and 2, respectively. The study [22] proposed a symmetric 40-Gb/s aggregate rate TWDM-PON system with the capability of simultaneous downstream differential phase shift keying (DPSK) signal demodulation to support 256 users with 50-km SMF transmission. This study [11] described schemes, experiments, and demos for upstream and downstream transmission in a future NG-PON2 compliant TWDM-PON system. It focused on the special attention on developing a low cost ONU, because the ONU is a major contributor to the total cost of a PON system.

However, to the best of the author knowledge, no study had been done on the comparative study between these plan options based on performance parameter which are Bit Error Rate (BER) and Optical Signal-to-Noise Ratio (OSNR) against the design parameters which are the distance and the received optical power (ROP).

The goal in this study is to design NG-PON2 architecture based on TWDM technique to support number of users up to 512 total number of users with extended distance of 80 km and 100 km. Based on the ITU-T recommendations G.989.1 [23] , NG-PON2 must support a split ratio of at least 1:256. Specific application and network engineering choices can require higher split ratios; therefore, the NG-PON2 design should not preclude supporting higher split ratios. Support for a higher number of ONUs per ODN enables a high degree of infrastructure sharing with longer reach. This proposed architecture allow the support of multi-service applications such as triple-play services for long distance and high number of users.

1.4 Aim and objectives

The aim of this research is to implement and evaluate the downstream performance of NG-PON2 based on TWDM-PON system.

The specific objectives are:

1- To design and develop NG-PON2 system based on TWDM-PON.
2- To demonstrate and evaluate three different ITU-T wavelength plans for downstream transmission.
3- To implement the triple play services which are data, voice and video on the developed TWDM-PON system for long distance and high number of users.

1.5 Scope

Figure 1.1 shows the scope of study covered in this master research. This thesis focuses on implementation of TWDM-PON technology in access network.

This Figure describes the PON-FTTH categories which classify to EPON, GPON and NG-PON where the later can be classified into two types which are NG-PON1 and NG-PON2. This work focuses on the developed NG-PON2. Conventional studies were conducted on how to improve system performance by deploying different multiplexing techniques, such as TDM, WDM and hybrid TDM/WDM. TWDM technique has been considered as the most promising solution for NG-PON2 network since it possesses high bandwidth in optical band. Also, TWDM technique can contribute to evaluate the increasing number of end users in ONU and achieving long reach fiber transmission line. The methodology is to design TWDM on NG-PON2 using VPI software and evaluate the three plan options on the TWDM-PON proposed system. The triple play services such as data, voice and video had been applied on the developed TWDM-PON system. Investigation and analyzing the effect of increasing the number of users with possible long reach distance had been conducted by observing the performance parameters such as OSNR and BER and design parameters which are ROP and distance.

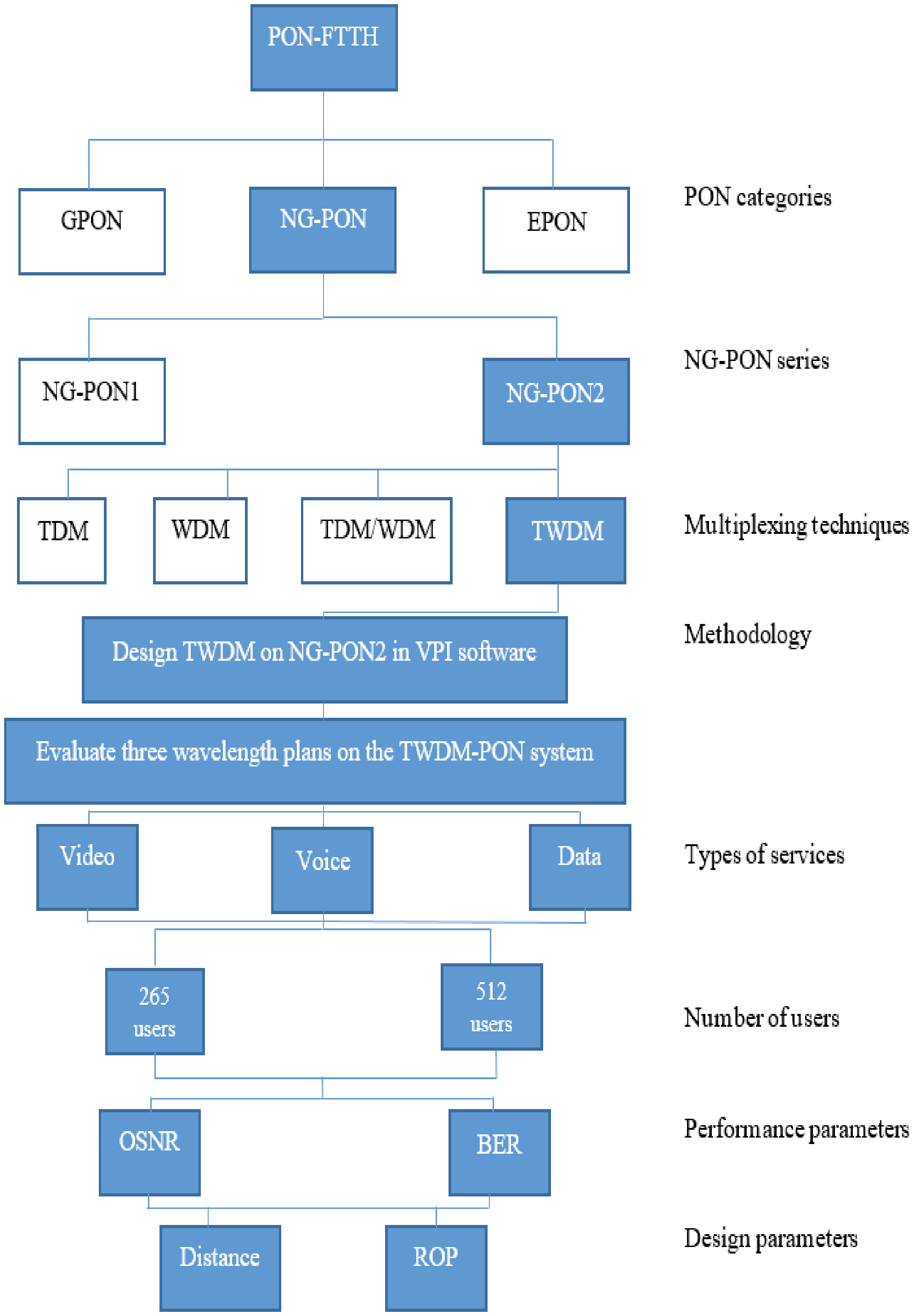

Figure 1.1 : The scope of study

1.6 Thesis Layout

In general, this thesis consists of five chapters.

Chapter 1, which is this current chapter, gives a general introduction of the topics, objective and defines the scope of work.

Chapter 2 introduces the fundamental backgrounds of PON architecture and describes the techniques previously proposed. Moreover, PON standards and NG-PON systems are reviewed and discussed with analysis of the NG-PON2 system being concisely described. Three plan options were explained in the end of this chapter in order to compare the performance of the NG-PON2 system.

Chapter 3 discusses the methodology in implementing the three plan options on the proposed architecture. Furthermore, detailed optical architecture in simulation is thoroughly described and the spectrum of transmitting signal is shown. The performance and design parameters of the system are then studied. In addition, the proposed model for TWDM-PON system is discussed with best wavelength plan to serve 256 and 512 users over 80 and 100 km transmission line.

Chapter 4 is devoted to the performance evaluation of the results of developed NG-PON2 system and comparative analysis of different plan options. The implementation of the three plan options are analyzed and results are extracted and compared. The second plan are selected to present the triple play services due to its best performance compared to other plans based on the proposed architecture in this thesis. The performance of proposed system for the second plan was achieved by supporting two different sets of number of users and long reach distance. The performance of the proposed system was analyzed by the performance parameters such as OSNR and BER against the design parameters such as distance and ROP.

The finding of this work is summarized and concluded in Chapter 5. The best option plan for this system has been identified and the performances of the proposed architecture are analyzed. Moreover, it includes the contribution of this thesis and the recommendation for further research work.

REFERENCES

[1] R. Q. Shaddad, A. Mohammad, S. A. Al-Gailani, A. Al-Hetar, and M. A. Elmagzoub, "A survey on access technologies for broadband optical and wireless networks," Journal of Network and Computer Applications, vol. 41, pp. 459-472, 2014.

[2] D. Kocher, "Investigation of FTTH architectures based on passive optical networks," Thapar University, 2012.

[3] M. S. Taqqu, W. Willinger, and R. Sherman, "Proof of a fundamental result in self-similar traffic modeling," ACM SIGCOMM Computer Communication Review, vol. 27, pp. 5-23, 1997.

[4] D. Sala and A. Gummalla, "PON functional requirements: services and performance," in IEEE 802.3 ah Meeting, 2001.

[5] M. Dorigo and C. Blum, "Ant colony optimization theory: A survey," Theoretical computer science, vol. 344, pp. 243-278, 2005.

[6] G. Kramer, M. De Andrade, R. Roy, and P. Chowdhury, "Evolution of optical access networks: Architectures and capacity upgrades," Proceedings of the IEEE, vol. 100, pp. 1188-1196, 2012.

[7] J.-i. Kani, F. Bourgart, A. Cui, A. Rafel, M. Campbell, R. Davey, "Next-generation PON-part I: Technology roadmap and general requirements," IEEE Communications Magazine, vol. 47, pp. 43-49, 2009.

[8] R. Kaler, P. Teotia, and R. Kaler, "Simulation of FTTH at 10Gbit/s for 8 OTU by GE-PON Architecture," Optik-International Journal for Light and Electron Optics, vol. 122, pp. 1985-1989, 2011.

[9] J. Prat, "Next–Generation FTTH Passive Optical Networks," Springer Science+ Business Media BV, 2008.

[10] B. Skubic, J. Chen, J. Ahmed, L. Wosinska, and B. Mukherjee, "A comparison of dynamic bandwidth allocation for EPON, GPON, and next-generation TDM PON," IEEE Communications Magazine, vol. 47, pp. S40-S48, 2009.

[11] W. Pöhlmann, B. Deppisch, T. Pfeiffer, C. Ferrari, M. Earnshaw, A. Duque and D. T. van Veen, "Low cost TWDM by wavelength- set division multiplexing," Bell Labs Technical Journal, vol. 18, pp. 173-193, 2013.

[12] S. Bindhaiq, A. S. M. Supa'at, and N. Zulkifli, "80-Gb/s wavelength stacked time and wavelength division multiplexing-passive optical network for the next generation-pon second stage," in 2014 IEEE 5th International Conference on Photonics (ICP), pp. 69-71, 2014.

[13] K.-i. Kitayama, Y. Yoshida, and R. Matsumoto, "Technology options beyond NG-PON2: IFDMA-WDM and OCDMA-WDM," in 19th Optoelectronics and Communications Conference (OECC) and the 39th Australian Conference on Optical Fibre Technology (ACOFT), p. 286, 2014.

[14] Z. Li, L. Yi, and W. Hu, "Key technologies and system proposals of TWDM-PON," Frontiers of Optoelectronics, vol. 6, pp. 46-56, 2013.

[15] Y. Luo, M. Sui, and F. Effenberger, "Wavelength management in time and wavelength division multiplexed passive optical networks (TWDM-PONs)," in Global Communications Conference (GLOBECOM), 2012 IEEE, pp. 2971-2976, 2012.

[16] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian and Y. Ma, "Time-and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON stage 2 (NG-PON2)," Journal of Lightwave Technology, vol. 31, pp. 587-593, 2013.

[17] M. Salleh, A. Supaat, S. Idrus, S. Yaakob, and Z. Yusof, "Flexible broadcasting and multicasting in 4λ× 10Gb/s AOPR TWDM PON system," Optik-International Journal for Light and Electron Optics, vol. 125, pp. 7030-7033, 2014.

[18] B. T. Scheme, "LTE: the evolution of mobile broadband," IEEE Communications magazine, vol. 45, pp. 44 -51, 2009.

[19] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited]," Journal of optical networking, vol. 4, pp. 737-758, 2005.

[20] S. Bindhaiq, N. Zulkifli, and A. M. Supa'at, "The transmission of symmetric 40Gb/s TWDM-based NG-PON2 utilizing delay interferometer (DI) for RSOA bandwidth enhancement," Optical Fiber Technology, vol. 30, pp. 65-71, 2016.

[21] N. Iiyama, J.-i. Kani, J. Terada, and N. Yoshimoto, "Two-phased capacity upgrade method for NG-PON2 with hierarchical star 8-QAM and square 16-QAM," in Optical Fiber Communication Conference, 2013.

[22] M. Bi, S. Xiao, H. He, L. Yi, Z. Li, J. Li and W. Hu, "Simultaneous DPSK demodulation and chirp management using delay interferometer in symmetric 40-Gb/s capability TWDM-PON system," Optics express, vol. 21, pp. 16528-16535, 2013.

[23] I.-T. G989.1, "40-Gigabit-capable passive optical networks (NG-PON2): General requirements " Recommendation ITU-T G.989.1, vol. 3, 2013.

[24] C. F. Lam, "Passive Optical Networks: Principles and Practice. San Diego, California.: Elsevier," 2007.

[25] R. Ramaswami, K. Sivarajan, and G. Sasaki, Optical networks: a practical perspective: Morgan Kaufmann, 2009.

[26] G. Kramer and G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," IEEE communications Magazine, vol. 40, pp. 66-73, 2002.

[27] G. Kramer, B. Mukherjee, and A. Maislos, " Ethernet Passive Optical Networks," IP OVER WDM, p. 229-275, 2004.

[28] E. Trojer, S. Dahlfort, D. Hood, and H. Mickelsson, "Current and next-generation PONs: A technical overview of present and future PON technology," Ericsson Review, vol. 2, pp. 64-69, 2008.

[29] R. Davey, J. Kani, F. Bourgart, and K. McCammon, "Options for future optical access networks," IEEE Communications Magazine, vol. 44, pp. 50-56, 2006.

[30] H. Nishiyama, Z. M. Fadlullah, and N. Kato, "Inter-layer fairness problem in TCP bandwidth sharing in 10G-EPON," IEEE Systems Journal, vol. 4, pp. 432-439, 2010.

[31] C. Chow, L. Xu, C. Yeh, H. Tsang, W. Hofmann, and M. Amann, "40-Gb/s Upstream Transmitters Using Directly Modulated 1.55- µm VCSEL Array for High-Split-Ratio PONs," IEEE Photonics Technology Letters, vol. 22, pp. 347-349, 2010.

[32] T. Tatsuta, Y. Yoshida, and Y. Maeda, "Standardization of G-PON (gigabit passive optical network) in ITU-T," NTT Tech. Rev, vol. 1, 2003.

[33] A. E. Kamal and B. F. Blietz, "A priority mechanism for the IEEE 802.3 ah EPON," in Communications, 2005. ICC 2005. 2005 IEEE International Conference on, pp. 1879-1883, 2005.

[34] A. Srivastava, "Next generation PON evolution," in Broadband Access Communication Technologies VII, International Society for Optics and Photonics, p. 509, 2013.

[35] S. Faruque, "Time Division Multiplexing (TDM)," in Radio Frequency Source Coding Made Easy, ed: Springer, pp. 91-118, 2015.

[36] I. Amiri, S. Alavi, M. Soltanian, N. Fisal, A. Supa'at, and H. Ahmad, "Increment of access points in integrated system of wavelength division multiplexed passive optical network radio over fiber," Scientific reports, vol. 5, 2015.

[37] E. T. López Pastor, "WDM/TDM PON bidirectional networks single-fiber/wavelength RSOA-based ONUs layer 1/2 optimization," 2013.

[38] A. Kurysheva, "All-fiber mach-zehnder interferometer for dwdm-pon bidirectional multiplexing," Universitat Politècnica de Catalunya, 2015.

[39] L. Yi, Z. Li, Y. Dong, S. Xiao, J. Chen, and W. Hu, "Upstream capacity upgrade in TDM-PON using RSOA based tunable fiber ring laser," Optics express, vol. 20, pp. 10416-10425, 2012.

[40] R. Heron, "Next generation optical access networks," in Access Networks and In-house Communications, pp 1-3, 2011.

[41] G. Talli and P. D. Townsend, "Hybrid DWDM-TDM long-reach PON for next-generation optical access," Journal of Lightwave Technology, vol. 24, p. 2827, 2006.

[42] S. Yao, B. Mukherjee, and S. Dixit, "Advances in photonic packet switching: an overview," IEEE Communications Magazine, vol. 38, pp. 84-94, 2000.

[43] R. Nelson and L. Kleinrock, "Spatial TDMA: A collision-free multihop channel access protocol," IEEE Transactions on communications, vol. 33, pp. 934-944, 1985.

[44] J. C. V. Micolta, J. C. V. Micolta, and J. C. V. Micolta, "Analysis of performances and tolerances of the second," IEEE Photonics Technology Letters, vol. 22, pp. 347 - 349, 2014.

[45] J. Prat and E. Ciaramella, "Low cost solutions implementing ultra-dense-WDM in access," in 2014 16th International Conference on Transparent Optical Networks (ICTON), pp. 1-2, 2014.

[46] A. Somani, Survivability and traffic grooming in WDM optical networks: Cambridge University Press, 2006.

[47] Y. Xiong, M. Vandenhoute, and H. C. Cankaya, "Control architecture in optical burst-switched WDM networks," IEEE journal on selected areas in communications, vol. 18, pp. 1838-1851, 2000.

[48] I. Kartiwa, S.-M. Jung, M.-K. Hong, and S.-K. Han, "20Gb/s WDM-OFDM-PON over 20-km single fiber uplink transmission using optical millimeter-wave signal seeding with rate adaptive bit-power loading," Optical Fiber Technology, vol. 19, pp. 231-235, 2013.

[49] T. P. Lee and C.-E. Zah, "Wavelength-tunable and single-frequency semiconductor lasers for photonic communications networks," IEEE Communications Magazine, vol. 27, pp. 42-52, 1989.

[50] H. Kobrinski and K.-W. Cheung, "Wavelength-tunable optical filters: Applications and technologies," IEEE Communications Magazine, vol. 27, pp. 53-63, 1989.

[51] K. Cheung, D. Smith, J. Baran, and B. Heffner, "Multiple channel operation of integrated acousto-optic tunable filter," Electronics letters, vol. 6, pp. 375-376, 1989.

[52] A. Sneh and K. M. Johnson, "High-speed continuously tunable liquid crystal filter for WDM networks," Journal of lightwave technology, vol. 14, pp. 1067-1080, 1996.

[53] K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," Journal of lightwave technology, vol. 15, pp. 1263-1276, 1997.

[54] M. Tachibana, R. Laming, P. Morkel, and D. Payne, "Erbium-doped fiber amplifier with flattened gain spectrum," IEEE Photonics Technology Letters, vol. 3, pp. 118-120, 1991.

[55] F. Forghieri, R. Tkach, A. R. Chraplyvy, and D. Marcuse, "Reduction of four-wave mixing crosstalk in WDM systems using unequally spaced channels," IEEE Photonics Technology Letters, vol. 6, pp. 754-756, 1994.

[56] C. A. Brackett, "Dense wavelength division multiplexing networks: Principles and applications," IEEE Journal on Selected Areas in Communications, vol. 8, pp. 948-964, 1990.

[57] K. Taguchi, H. Nakamura, K. Asaka, S. Nakano, S. Kimura, and N. Yoshimoto, "100-ns λ-selective burst-mode transceiver for 40-km reach symmetric 40-Gbit/s WDM/TDM-PON," in 39th European Conference and Exhibition on Optical Communication (ECOC 2013), 2013.

[58] S. Ihara, S. Yoshima, T. Suehiro, M. Noda, E. Igawa, M. Nogami and J. Nakagawa, "Experimental demonstration of C-band burst-mode transmission for high power budget (64-split with 40km distance) TWDM-PON systems," in IET Conference Proceedings, pp. 1-3, 2013.

[59] G. Yoffe, S. Zou, S. Rishton, R. Olson, M. Emanuel, and B. Pezeshki, "Widely-tunable 30mW laser source with sub-500kHz linewidth using DFB array," in LEOS 2008-21st Annual Meeting of the IEEE Lasers and Electro-Optics Society, pp. 892-893, 2008.

[60] N. Cheng and F. Effenberger, "WDM PON: systems and technologies," in European Conference and Exhibition on Optical Communication, pp. 4-26, 2010.

[61] L. Yi, Z. Li, M. Bi, H. He, W. Wei, S. Xiao, "Experimental demonstrations of symmetirc 40-Gb/s TWDM-PON," in Information, Communications and Signal Processing (ICICS) 2013 9th International Conference on, pp. 1-3, 2013.

[62] J. Prat, J. Lazaro, P. Chanclou, R. Soila, A. M. Gallardo, A. Teixeira and I. Tomkos, "Results from EU project SARDANA on 10G extended reach WDM PONs," in Optical Fiber Communication Conference, pp. 1-3, 2010.

[63] R. Goyal and R. Kaler, "A novel architecture of hybrid (WDM/TDM) passive optical networks with suitable modulation format," Optical Fiber Technology, vol. 18, pp. 518-522, 2012.

[64] J. Chen and L. Wosinska, "Analysis of protection schemes in PON compatible with smooth migration from TDM-PON to hybrid WDM/TDM-PON," Journal of optical networking, vol. 6, pp. 514-526, 2007.

[65] F.-T. An, K. S. Kim, D. Gutierrez, S. Yam, K. Shrikhande, and L. G. Kazovsky, "SUCCESS: A next-generation hybrid WDM/TDM optical access network architecture," Journal of lightwave technology, vol. 22, pp. 2557-2559, 2004.

[66] D. J. Shin, D. K. Jung, H. S. Shin, J. W. Kwon, S. Hwang, Y. Oh and C. Shim, "Hybrid WDM/TDM-PON with wavelength-selection-free transmitters," Journal of Lightwave Technology, vol. 23, pp. 187-190, 2005.

[67] C. Bock, J. Prat, and S. D. Walker, "Hybrid WDM/TDM PON using the AWG FSR and featuring centralized light generation and dynamic bandwidth allocation," Journal of Lightwave Technology, vol. 23, pp. 3981-3983, 2005.

[68] J. S. Shaik and N. Patil, "FTTH deployment options for telecom operators," Sterlite Optical Technologies Ltd., White Paper, pp. 1-9, 2005.

[69] C. Chow, J. Sung, C. Hsu, and C. Yeh, "Enabling technologies and signal processing for NG-PON2 and future WDM-PON," in 2013 9th International Conference On Information, Communications And Signal Processing (ICICS), pp. 1-2, 2013.

[70] J.-i. Kani, F. Bourgart, A. Cui, A. Rafel, M. Campbell, R. Davey and S. Rodrigues, "Next-generation PON-part I: Technology roadmap and general requirements," IEEE Communications Magazine, vol. 47, pp 43-49, 2009.

[71] F. J. Effenberger, "The XG-PON system: Cost effective 10 Gb/s access," Journal of lightwave technology, vol. 29, pp. 403-409, 2011.

[72] J.Kim , J. J. Lee, S. Lee and Kim, Y. S., "Physical Media Dependent Prototype for 10- Gigabit- Capable PON OLT." ETRI Journal, vol. 35, pp. 245-252, 2013.

[73] E. Wong, C. M. Machuca, and L. Wosinska, "Survivable Hybrid Passive Optical Converged Network Architectures Based on Reflective Monitoring," Journal of Lightwave Technology, vol. 34, pp. 4317-4328, 2016.

[74] L. Yi, Z. Li, M. Bi, W. Wei, and W. Hu, "Symmetric 40-Gb/s TWDM-PON with 39-dB power budget," IEEE Photonics Technology Letters, vol. 25, pp. 644-647, 2013.

[75] S. Bindhaiq, N. Zulkifli, A. S. M. Supa'at, and R. Q. Shaddad, "Capacity improvement of TWDM-PONs exploiting the 16-QAM technique for downstream side with a nonlinearity effect study for upstream DML," Journal of Optical Communications and Networking, vol. 7, pp. 1018-1024, 2015.

[76] C.-H. Yeh, C.-W. Chow, M.-H. Yang, and D.-Z. Hsu, "A flexible and reliable 40-Gb/s OFDM downstream TWDM-PON architecture," IEEE Photonics Journal, vol. 7, pp. 1-9, 2015.

[77] I. Rec, "G. 989.3,"40-Gigabit-Capable Passive Optical Networks 2 (NG-PON2): Transmission Convergence (TC) Layer Specification," Under Study, 2015.

[78] G. ITU, "984.1: Gigabit-capable Passive Optical Networks (GPON): General characteristics," ITU-T, March, 2008.

[79] S. Bindhaiq, A. S. M. Supa, N. Zulkifli, A. B. Mohammad, R. Q. Shaddad, M. A. Elmagzoub, "Recent development on time and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation passive optical network stage 2 (NG-PON2)," Optical Switching and Networking, vol. 15, pp. 53-66, 2015.

[80] Y. Ma, Y. Qian, G. Peng, X. Zhou, X. Wang, J. Yu, "Demonstration of a 40Gb/s time and wavelength division multiplexed passive optical network prototype system," in Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012 and the National Fiber Optic Engineers Conference, pp. 1-3, 2012.

[81] L. Yi, Z. Li, Y. Dong, S. Xiao, and W. Hu, "80/10Gb/s downstream/upstream capacity multi-wavelength TDM-PON," in Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2012 8th International Symposium on, pp. 1-4, 2012.

[82] D. Nesset, "NG-PON2 technology and standards," Journal of Lightwave Technology, vol. 33, pp. 1136-1143, 2015.

[83] L. F. Henning, R. M. Maria do Carmo, P. Monteiro, and A. de AP Pohl, "Colourless ONU based on self seed signal RSOA in a WDM-PON," in Telecommunications Network Strategy and Planning Symposium (Networks), 2014 16th International, pp. 1-6, 2014.

[84] S. Liu, X. Wang, W. Zhang, G. Shen, and H. Tian, "An Adaptive Activated ANN Equalizer Applied in Millimeter-Wave RoF Transmission System," IEEE Photonics Technology Letters, pp.1935-1938, 2017.

[85] G. Breed, "Bit error rate: Fundamental concepts and measurement issues," High Frequency Electronics, vol. 2, pp. 46-47, 2003.

[86] M. Jeruchim, "Techniques for estimating the bit error rate in the simulation of digital communication systems," IEEE Journal on Selected Areas in Communications, vol. 2, pp. 153-170, 1984.

[87] What should the OSNR values be in DWDM networks? [Online]. Available: http://www.exfo.com/corporate/blog/2012/osnr-values-dwdm-networks

[88] D. Kilper, S. Chandrasekhar, L. Buhl, A. Agarwal, and D. Maywar, "Spectral monitoring of OSNR in high-speed networks," in Optical Communication, 2002. ECOC 2002. 28th European Conference on, pp. 1-2, 2002.

[89] G. Jacobsen, L. Gillner, and O. Fransson, "On the use of OSNR for BER monitoring in WDM systems and optical networks," Journal of optical communications, vol. 21, pp. 20-23, 2000.

[90] S. V. Kartalopoulos, Free space optical networks for ultra-broad band services: John Wiley and Sons, 2011.

[91] I. SG15, "Gigabit-Capable Passive Optical Networks (GPON), ITU-T Standard G-Series G. 984. x , pp. 1-7, 2008.

[92] K. Rayner, "Understanding eye movements in reading," Scientific Studies of Reading, vol. 1, pp. 317-339, 1997.