ALL OPTICAL PACKET ROUTING TIME WAVELENGTH DIVISION MULTIPLEXING PASSIVE OPTICAL NETWORK

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ABSTRACT

Time Wavelength Division Multiplexing (TWDM) Passive Optical Network (PON) is a combination of both Time Division Multiplexing (TDM) and Wavelength-Division Multiplexing (WDM) technologies. The TWDM PON system can provide scalable and efficient wavelength management in WDM-PON network and at the same time can reduce numbers of aggregation node in metro network level. In this study, a new All-Optical Packet Routing (AOPR) TWDM PON system is designed to provide more flexibility of data delivery for each PON port and more bandwidth to each subscriber at multiple PON Optical Distribution Network (ODN) link. By proposing broadcasting, multicasting, and multiplexing technique in downstream signal, the system is capable to support full degree of flexibility in managing efficient dynamic bandwidth allocation. To achieve flexible packet routing between multiple PON ports and multiple PON ODN links TWDM PON architecture, most of the proposed system used tunable transceiver in optical line terminal. This design will cause the attractiveness of the PON system, which is able to broadcast and multicast packet within the entire PON system limited only at single PON link. The proposed AOPR module was designed to incorporate fixed-type wavelength Optical Line Terminal (OLT) transmitter with Continuous Wave (CW) Pump Probe Signal (PPS) module. This design used high-speed wavelength selective switch (WSS) or ALL ON method to support high speed wavelength switching or all broadcast signal to replace a wavelength tuning feature in tunable OLT transmitter. The proposed architecture has been designed using the multicasting cross-gain modulation (XGM) method. In this proposed design, XGM function located in the OLT system becomes a part of the AOPR OLT transmitter. The arrangement of this design aims to generate single or multiple wavelengths in a downstream direction in each OLT PON port. The system is designed and simulated using VPI photonic software followed by experimental verification in the laboratory. This design showed the ability of the system to perform flexible packet routing function by using WSS method with 38 dB allowable link loss margin in the system at 10 Gbps at Bit Error Rate (BER) of 10^{-3}. By using 16λ, 10Gbps downstream bandwidth can serve up to 2000 users at 20km. In regard to handling the broadcasting or multicasting flexible function with ALL ON method in the system, the result revealed that the proposed system can support 160Gbps broadcast downstream bandwidth to serve up to16 PON links using 16λ. The proposed architecture shows this method will minimise an inventory issue and reduce point of error caused by different OLT PON port transmitter wavelength during system installation and maintenance. The proposed AOPR OLT module has high potential to be used in the future extended TWDM PON access network.

ABSTRAK

Pembahagian Kombinasi Masa dan Panjang Gelombang (TWDM) Rangkaian Optik Pasif (PON) adalah gabungan teknologi Pembahagian Kombinasi Masa (TDM) dan Pembahagian Kombinasi Panjang Gelombang (WDM). Sistem TWDM PON berupaya memberikan skalabiliti dan amat berkesan dalam fungsi pengurusan panjang gelombang dalam rangkaian WDM-PON serta pada masa yang sama boleh mengurangkan bilangan pengagregatan nod di peringkat rangkaian metro. Dalam kajian ini, sistem Aliran Paket Optik Menyeluruh (AOPR) TWDM PON direka untuk memberi fleksibiliti dan jalur lebar tambahan dalam penghantaran data dari setiap liang PON kepada setiap pelanggan dalam berbilang Rangkaian Agihan Optik (ODN). Dengan mencadangkan teknik siaran, siaran terpilih dan penggabungan isyarat halaan menurun dari Terminal Talian Optik (OLT) ke Unit Rangkaian Optik (ONU), sistem ini mampu untuk memberikan fleksibiliti dalam pengurusan peruntukan jalur lebar yang lebih dinamik dan berkesan. Kebanyakan sistem TWDM PON yang dicadangkan mengunakan pemancar boleh laras pada OLT untuk mencapai fleksibiliti pada aliran data diantara setiap liang PON dan ODN. Namun, reka bentuk ini akan menghadkan kelebihan kepada sistem PON, di mana ia tidak mampu melaksanakan fungsi siaran secara sepenuhnya di dalam keseluruhan sistem PON. Modul AOPR yang dicadangkan telah direka untuk menggabungkan panjang gelombang bernilai tetap pada pemancar OLT bersama modul Gelombang Berterusan (CW) Isyarat Pam Kuar (PPS). Reka bentuk ini menggunakan kaedah suis pilihan panjang gelombang pada kelajuan tinggi (WSS) atau SEMUA AKTIF untuk menyokong pensuisan panjang gelombang pada kelajuan tinggi serta semua isyarat siaran untuk menggantikan fungsi pelarasan panjang gelombang pada pemancar OLT. Seni bina yang dicadangkan ini menggunakan kaedah siaran terpilih modulasi gandaan silang (XGM) di mana fungsi ini menjadi sebahagian daripada pemancar AOPR OLT. Susunan reka bentuk ini bertujuan menghasilkan panjang gelombang tunggal atau berbilang mengikut arah aliran isyarat menurun dari setiap liang PON OLT. Sistem ini direka dan disimulasi dengan menggunakan perisian VPI dan diikuti oleh pengesahan melalui ujikaji di dalam makmal. Keputusan menunjukkan keupayaannya untuk melaksanakan fungsi aliran paket yang fleksibel dengan menggunakan kaedah WSS dengan nilai kehilangan kuasa optik dalam talian sebanyak 38 dB pada kelajuan 10 Gbps dengan Kadar Ralat Bit (BER) sebanyak 10^{-3}. Dengan menggunakan 16λ, isyarat jalur lebar dari OLT ke ONU dengan kelajuan 10Gbp boleh memberi perkhidmatan kepada pengguna seramai 2000 orang dalam jarak 20km. Merujuk kepada pengendalian fungsi fleksibel pada siaran penuh dan terpilih dengan menggunakan kaedah SEMUA AKTIF, hasilnya menunjukkan sistem ini boleh menyokong siaran penuh aliran menurun dengan kelajuan 160Gbps untuk memberi perkhidmatan kepada 16 PON dengan menggunakan 16λ. Daripada hasil yang diperolehi, sistem yang dicadangkan ini mampu mengurangkan kelambatan masa yang disebabkan oleh pelarasan panjang gelombang dari OLT ke ONU. Di samping itu, kaedah ini akan mengurangkan isu inventori dan dapat mengurangkan kesilapan yang disebabkan oleh perbezaan panjang gelombang pada liang PON OLT yang boleh berlaku semasa proses pemasangan dan penyelenggaraan. Modul AOPR OLT yang dicadangkan mempunyai potensi yang tinggi untuk digunakan sebagai nilai tambah kepada sistem TWDM PON dalam rangkaian capaian pada masa akan datang.

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A/W	-	Amperes per watt
AGC-SOA	-	Adjustable Gain-Clamped Semiconductor Optical Amplifier
ALC	-	Automatic level control
APON	-	ATM(-Based) Passive Optical Network
ASE	-	Amplified Spontaneous Emissions
AWG	-	Arrayed Waveguide Grating
B&M	-	Broadcasting and Multicasting
B&S	-	Broadcast and select
B2B	-	Back to Back
BER	-	Bit Error Rate/Ratio
BERT	-	Bit Error Rate Test (Or Tester)
BPON	-	Broadband Passive Optical Network
B-Tx	-	Burst Transmitter
CD	-	Chromatic Dispersion
CO	-	Central Office
CW	-	Continuous Wave
CW-PPS	-	Continuous Wave- Pump probe signal
DBA	-	Dynamic Bandwidth Allocation
DCA	-	Digital Communications Analyzer
DFB	-	Distributed Feedback Laser
DML	-	Directly Modulated Laser
DPSK	-	Differential Phase Shift Keying
DS	-	Downstream Signal
DS/US	-	Downstream Signal Upstream Signal
DWBA	-	Dynamic Wavelength and Bandwidth Allocation
DWDM	-	Dense Wavelength Division Multiplexing
EAM	-	Electro Absorb Modulation

EDFA	-	Erbium-Doped Fiber Amplifier
EML	-	Externally modulated laser
EPON	-	Ethernet (-Based) Passive Optical Network
ER	-	Extinction Ratio
FEC	-	Forward Error Correction
FLS	-	Fixed Laser Source
FMW	-	Four Wave Mixing
FSAN	-	Full Service Access Network
FSR	-	Free spectral range
GaAs	-	Gallium arsenide
Gbit/s	-	Gigabits per second
GHz	-	GigaHetz
GPON	-	Gigabit Passive Optical Network
GVD	-	Group velocity dispersion
ID	-	Identification
IEEE	-	Institute Of Electrical And Electronics Engineers
IL	-	Insertion Loss
InP	-	Indium phosphide
ISI	-	Intersymbol Interference
ITU-T	-	International Telecommunication Union-Telecommunications
L2	-	Open Systems Interconnection (OSI) Layer 2
L3	-	Open Systems Interconnection (OSI) Layer 3
LD	-	Laser Diode
M&R	-	Multiplexing and Routing
MAC	-	Media Access Control (IEEE 802)
MPOS	-	Multi- Protocol Optical Switch
MW	-	Multiple Wavelengths
NG-PON	-	Next Generation Passive Optical Network
NRZ	-	Non-Return To Zero
NTT	-	Nippon Telegraph and Telephone
O/E	-	Optical to Electrical conversion
O/E/O	-	Optical to Electrical to optical conversion
OA	-	Optical Amplifiers

OAN	-	Optical Access Network
OCM	-	Optical Channel Monitor
ODN	-	Optical Distribution Network
OFDM	-	Orthogonal Frequency Division Multiplexing
OLT	-	Optical Line Terminal
OMA	-	Optical Modulation Amplitude
ONT	-	Optical Network Terminal
ONU	-	Optical Node Unit
OOB	-	Out of band
OOK	-	On Off Keying
OPM	-	Optical Performance Monitor
OPS	-	Optical Passive Splitter
OSA	-	Optical Spectrum Analyzer
OSI	-	Open Systems Interconnection
OSNR	-	Optical signal to noise ratio
OTDM	-	Optical time domain multiplexing
P2P	-	Point to Point
PAYG	-	Pay As You Grow
PDL	-	Polarization Dependence Loss
PIC	-	Photonic in Circuit
PIN	-	Positive-Intrinsic-Negative
PL	-	PON link
PMD	-	Physical Media-Dependent
PON	-	Passive Optical Network
PPS	-	Pump Probe Signal
PRBS	-	Pseudo-Random Bit Sequence
QD-SOA	-	Quantum Dot SOA
R&D	-	Research and Development
RIN	-	Relative Intensity Noise
RN	-	Remote Node
RSOA	-	Reflective Semiconductor Optical Amplifier
RSOF	-	Red Shift Optical Filter
RX	-	Receive

SGC	-	Synchronized gain-clamping
SMSR	-	Side mode suppression ratio
SOA	-	Semiconductor optical amplifier
SR	-	Short Range
TDM	-	Time Division Multiplexing
TDM/WDM	-	Time Domain Multiplexing Wavelength Division Multiplexing
TDM-PON	-	Time Domain Multiplexing Passive Optical Network
TL	-	Tunable Laser
TLS	-	Tunable Laser Source
TWDM	-	Time Wavelength Division Multiplexing
TWLS	-	Tunable wavelength laser source
TX	-	Transmit
US	-	Upstream signal
VOA	-	Varying Optical Attenuator
VPN	-	Virtual Private Network
W&R	-	Wavelength routing
WB&M	-	Wavelength broadcasting and multicasting
WB&S	-	Wavelength broadcast and select
WDM	-	Wavelength-Division Multiplex
WDM-PON	-	Wavelength Division Multiplexing Passive Optical Network
WM	-	Wavelength Multiplexing
WM&B	-	Wavelength Multicast and Broadcast
WM&R	-	Wavelength multiplex and routing
WR	-	Wavelength routing
WS	-	Wavelength select
WSS	-	Wavelength select switch
WTF	-	Wavelength tuning free
XGM	-	Cross Gain Modulation
XG-PON	-	10G Passive Optical Network
XPM	-	Cross Phase Modulation

LIST OF SYMBOLS

P_{in}	-	Input power
P_{out}	-	Output power
λ_S	-	Center Frequency OLT transmitter
λ_T	-	Center Frequency CW PPS
h	-	Planck constant
v	-	Probe signal frequency
I_{th}	-	Current fluctuation is induced by thermal noise
q	-	Electron charge
n_{sp}	-	Spontaneous emission factor
Δ_v	-	Effective receiver bandwidth
fsr	-	Frequency spectral range
IL	-	Insertion loss
B	-	Bit rate
R	-	Responsivity
Be	-	Electrical bandwidth filter
Bo	-	Optical bandwidth filter
G_{sat}	-	Saturation Gain
G_{sat_Multi}	-	Saturation Gain for broadcasting/multicasting
σ_{shot}	-	Shot noise
σ_{s_sp}	-	Signal spontaneous noise
σ_{sp_sp}	-	Spontaneous spontaneous noise
σ_{th}	-	Thermal noise
σ_{conv}	-	Wavelength conversion noise
G_o	-	Unsaturated material gain
r	-	Extinction ratio
r_{out}	-	Extinction ratio output signal
P_{probe}	-	Pump probe power (CW transmit power)

P_{pump}	-	Pump power (OLT transmit power)
P_{sat}	-	Saturation output power
G_{multi}	-	Saturation Gain for broadcasting or multicasting
n	-	No of PON link
β_{total}	-	Total Noise per system
β_{soa_total}	-	Total SOA noise
β_{rx_total}	-	Total receiver Noise
P_b	-	Power budget
P_{rec}	-	Received power
P_{sen}	-	Received sensitivity power
C_L	-	Total loss
Ms	-	System margin
W_p	-	Wavelength penalty
α_f	-	Optical fiber loss
L	-	Total ODN loss
α_{con}	-	Connector loss
α_{splice}	-	Splice loss
α_{split}	-	Single optical splitter loss
α_{total_split}	-	Maximum total optical splitter loss
s	-	Numbers of the optical splitter cascading
s_{max}	-	Maximum number of optical splitter cascading
k	-	Total number of user / split ratio per optical splitter
k_{max}	-	Maximum number of user / split ratio per optical splitter
j	-	Total number of users per PON link
m	-	Total number of users per AOPR TWDM PON system
y	-	Number of optical splitter stage
Δ_x	-	Band Gap delay
Δ_t	-	Tuning delay

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

With the demand for higher bandwidth and high quality of services expected to increase in the next few years (Cisco System, 2011; Cisco System, 2013; Middleton, 2010), network operators are starting to migrate their system from legacy system to new technology that is capable to support more bandwidth and offer more reliable network. This system upgrade will affect the entire network from access, metro to the core network. The migration of system must also consider the integration of new and legacy system to ensure smooth upgrade planning and to support the current as well as the future network demands. However, most telecommunication service providers invest multimillion dollars to deploy passive optical network (PON) system such as (Ethernet Passive Optical Network (EPON)/ Gigabit Passive Optical Network (GPON)) in their network. In order to maintain the investment of the current network, the evolution of PON towards next-generation PON must be able to coexist with the current EPON/GPON. This initiative was further studied by Andrade *et al.* (2011); Kani *et al.* (2009); Kramer, (2009) and Teixeira, (2010). It was found that the main factor that contributes to the coexistence of the network and system, is using the existing optical distribution network (ODN) and avoiding the usage of the same wavelength allocated by current PON technology.

Full Service Access Network (FSAN) group has been studying next-generation solutions to facilitate high bandwidth provision, large split ratio, and extended reach (Kani and Nakamura, 2012). In addressing next generation passive optical network 1 (NG-PON1), whose main focus is to develop a PON that is compatible with an operational GPON, International Telecommunication Union–Telecommunication (ITU-T) with FSAN has defined XG-PON1 as part of the NG-PON1 standardization path, with its features elaborated in the ITU-T G.987 recommendations (Wong, 2012). There are two types of NG-PON1 developed by ITU-T standard. This technology is based on the upstream line rate: XG-PON1 and XG-PON2, featuring a 2.5 and a 10 Gbit/s upstream path, respectively. After finalizing the XG-PON1 basic specifications, which are being successfully adopted by ITU-T and standardized in G.987 document series, the group is now focusing on the additional features and tools for extending the applicability of the XG-PON technologies. Moreover, under the generic term NG-PON2, the task group has started an investigation on the upcoming technologies which are able to (i) increase bandwidth further and (ii) solve the issues faced in the "1G" and "10G" PON technology deployments. In 2010, FSAN began investigating such NG-PON2 technologies to address the user, services, and network requirements. NG-PON2 also considers new fibre architectures to harness the benefits of the maturing WDM technologies and their necessary adaptations for the access network (Andrade *et al.*, 2011; Kani *et al.*, 2009; Kani and Nakamura, 2012; Luo *et al.*, 2012; Wong, 2012)

Operators provide a general set of NG-PON2 requirements. The requirements to support NG-PON2 come from several aspects including user requirements, services requirements, and network requirements (Chanclou *et al.*, 2012; Effenberger *et al.*, 2009; Effenberger *et al.*, 2010; Kani *et al.*, 2009; Luo *et al.*, 2012). To support higher bandwidth demand in the future, telecommunications companies expect NG-PON2 system to support at least 40 Gbit/s aggregate capacity per feeder fibre in the downstream, and at least 10 Gbit/s in the upstream. On top of that, to support a longer reach of fibre distance between optical line terminal (OLT) and optical network unit (ONU), the maximum fibre reach for NG-PON2 should be at least 40 km, and a maximum differential fibre distance of up to 60 km should also be supported. Optical distribution networks (ODNs) that are typically deployed in GPON today range between 16 and 128 ONUs. NG-PON2 should be (Chanclou *et* *al.*, 2012) capable to operate in available spectrums that are not used by legacy PONs to allow coexistence, smooth migration network, and provide high level of flexibility that makes the coexistence of GPON, XG-PON, and NG PON2 possible. The legacy ONU and OLT must remain unchanged and do not require an additional filter to protect against interference from NG-PON2 signals in any migration scenario with coexistence. On the basis of the general requirements gathered from major telco operators, there have been many different system configurations proposed by research institutes and vendors to support aggregate data rate beyond 40 Gbit/s. In April 2012, FSAN selected TWDM PON system as a primary solution to be deployed in NG-PON2 (Luo *et al.*, 2013), supported with P2P WDM PON to support mobile backhaul system.

1.2 Problem Statement

The main challenge of the architecture is to have the flexibility and scalability of the time and wavelength division multiplexed passive optical network (TWDM) PON to support more numbers of users and manage the burst and fluctuation of low and high bandwidth traffic in access network. There are many approaches used to support high numbers of users and long-reach system (Shea and Mitchell, 2009; Taguchi *et al.*, 2010; Talli and Townsend, 2006). One of the approaches is to design the system by managing multiple PON link interconnects with multiple PON ports within a single TWDM PON system (Feng *et al.*, 2011; Taguchi *et al.*, 2013; Cheng *et al.*, 2013). Nevertheless, the problems of this architecture are the following:

- Flexibility of the system to handle full function of broadcasting or multicasting and at the same time to handle multiplexing of multiple wavelengths with different PON ports at different PON links within a single TWDM PON system decreases.
- High cost of fibre deployment to support an existing ODN and fibre infrastructure.

- Complex design of the system to handle multiple access technologies thereby GPON, XG-PON, and TWDM PON at different PONs.

In designing a flexible TWDM PON system, most of the proposed architectures use tunable laser source (TLS) (Bock *et al.*, 2005; Nakamura *et al.*, 2013) or multiple fixed multi-wavelength (FMW) (Cheng *et al.*, 2013; Cheng *et al.*, 2014) transmitter in OLT PON port that allows flexible wavelength routing (WR) and multiplexing of the signal in downstream signal. However, tunable laser source (TLS) signals have the following limitations:

- In providing full broadcast or multicast within entire TWDM PON system as TLS will transmit only single wavelength and this signal will be routed only to a certain single PON link.
- To re-route certain packet at a different PON link, TLS requires certain time to tune the wavelength (Buus and Murphy, 2006; Fabrega *et al.*, 2011), which will cause wavelength tuning delay in the system, thereby affecting the performance of the system.

However, adopting a multi-channel wavelength transmitter, the following problems are encountered:

- High numbers of OLT transmitter connected to a single PON port, which will incur an additional cost to the system.
- Different types of transmitter will introduce inventory issues and will add the possibility of human error during the system installation or maintenance.

1.3 Motivation

Motivated by the benefit of flexible TWDM PON system architecture, this study discusses the development of flexible TWDM PON system to support multiple PON link interconnects with multiple PON ports. This will allow the scalable system to support high numbers of users and large coverage area in the access network. In addition this will support full degree of flexibility to manage highly efficient dynamic bandwidth allocation and to support burst and fluctuation traffic at low- and high-bandwidth demand in the access network. Subsequently, to reduce the capital expense and operational expense, by leveraging an existing fibre cable and maintaining the optical splitter in the remote node, a service provider is able to use the existing fibre and ODN deployment in access network, which will reduce the cost of system and the deployment time in brown field network. This method will allow coexistence of TWDM PON system with legacy GPON and XG-PON systems and provide a smooth migration from legacy to TWDM PON. Besides maintaining an existing infrastructure, pay-as-you-go (PAYG) design concept will reduce an initial investment of the service provider by allowing the system to work with minimum numbers of PON ports and making it scalable to increase the number of PON ports according to the demand of the users. Meanwhile, using fixed wavelength and minimum number of PON port transmitters in OLT system will reduce the system cost, inventory issue, and chances of error in the system during fibre installation. In addition, to support green system initiative, the capability of the OLT system to turn OFF certain OLT PON ports while the total bandwidth usage is low will allow power-saving mode to be implemented in the OLT module. Moreover, the flexible design of TWDM PON architecture to integrate with aggregation and routing functions in PON system will reduce the numbers of aggregation ports in the metro network, which will reduce the capacity of layer 2 metro switch that turns to power saving for overall system in the network.

1.4 Research Objectives

The main objectives of this research was to design an all-optical packet routing (AOPR) TWDM PON system architecture to support full degree of flexible function in TWDM PON system to support flexible packet routing, packet multiplexing, packet broadcasting and multicasting functions, and to combine both multiplexing and broadcasting functions.

There are several goals to achieve this objective.

1. To design and develop AOPR OLT module using all-optical wavelength conversion with cross-gain modulation (XGM) and multicasting XGM to support up to 2000 users with 160Gbps downstream bandwidth
2. To design and develop 3R (re-routing, re-convert, and re-amplified) function in AOPR OLT module to support high allowable link loss margin in the system
3. To design free (zero) wavelength tuning delay in the downstream system by implementing the high-speed wavelength select switch as a pump probe signal (PPS) in AOPR OLT module

1.5 Scope of Works

The objective of this work is to concentrate at PON system technology for hybrid TWDM PON. Figure 1.1 shows the scope of work to be carried out in this study. The previous work of flexible design of TWDM PON will be reviewed and investigated to support and align it with NG-PON2 system requirements. Two designs of proposed TWDM PON architecture have been reviewed in this study: the first is static and the second is dynamic TWDM PON system architecture. To support flexible and scalable system design architecture, the study will focus and exploit dynamic-type PON architecture supported with multiple PON links interconnected with multiple PON ports in the TWDM PON system; this design will be used as a base design in this proposed system architecture. On the basis of the literature review, flexible multiple PON links are classified into four categories of flexible TWDM PON system architecture: (i) broadcast and select (B&S), (ii) wavelength-routed (WR) and B&S (W&R and B&S), (iii) wavelength multiplexing and routing and broadcast and select (WM&R and B&S), and (iv) W&R system architecture. This work will focus on WM&R and B&S system design architecture. Two types of transmitter were used in OLT PON port to support full flexible design in TWDM PON architecture,: TWLS and fixed-wavelength laser source (FWLS). In this proposed design, the system applies single OLT transmitter FWLS in OLT PON port to eliminate the problems discuss earlier. This proposed system architecture had full degree of flexibility to support four functions of wavelength multiplexing (WM), WR, wavelength broadcasting and multicasting (WB&M), and hybrid WM and WB&M functions. To design all-optical WR and WB&M, it is suggested that XGM technique instead of XPM or FWM should be used to reduce the complexity of the system design to support the required function. In managing single or multiple wavelengths to support WR and WB&M functions, WSS PPS and All ON PPS modules were design in this study. All the experimental and simulation analyses of the system will be focused on downstream signal in this study, and physical performance will be examined.

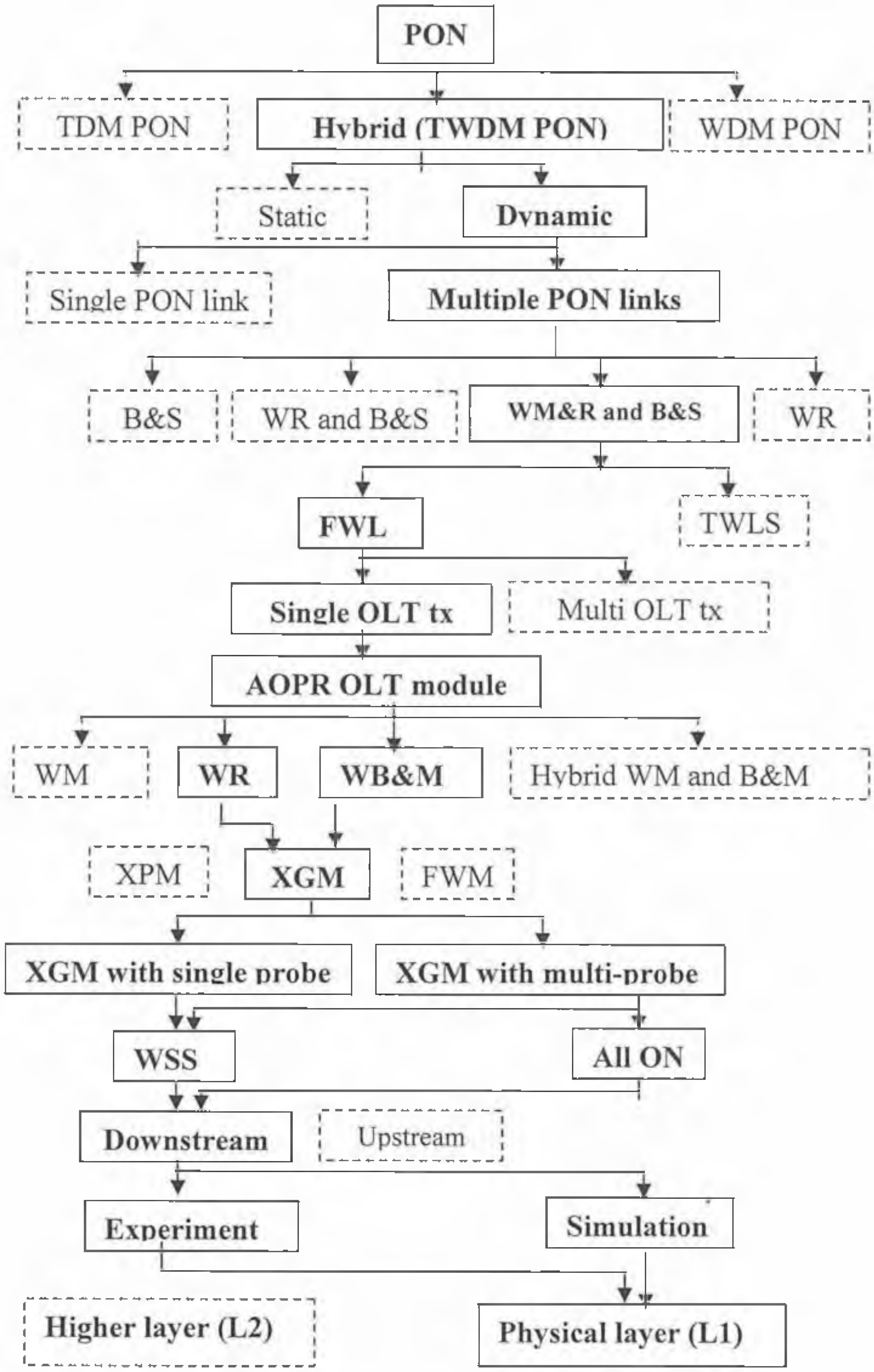

Figure 1.1 Scope of work to be carried out in this thesis

1.6 Research Methodology

This section will cover all the issues and approach considerations towards this project. To address the research objectives, a work flow diagram of the research is constructed and presented in Figure 1.2.

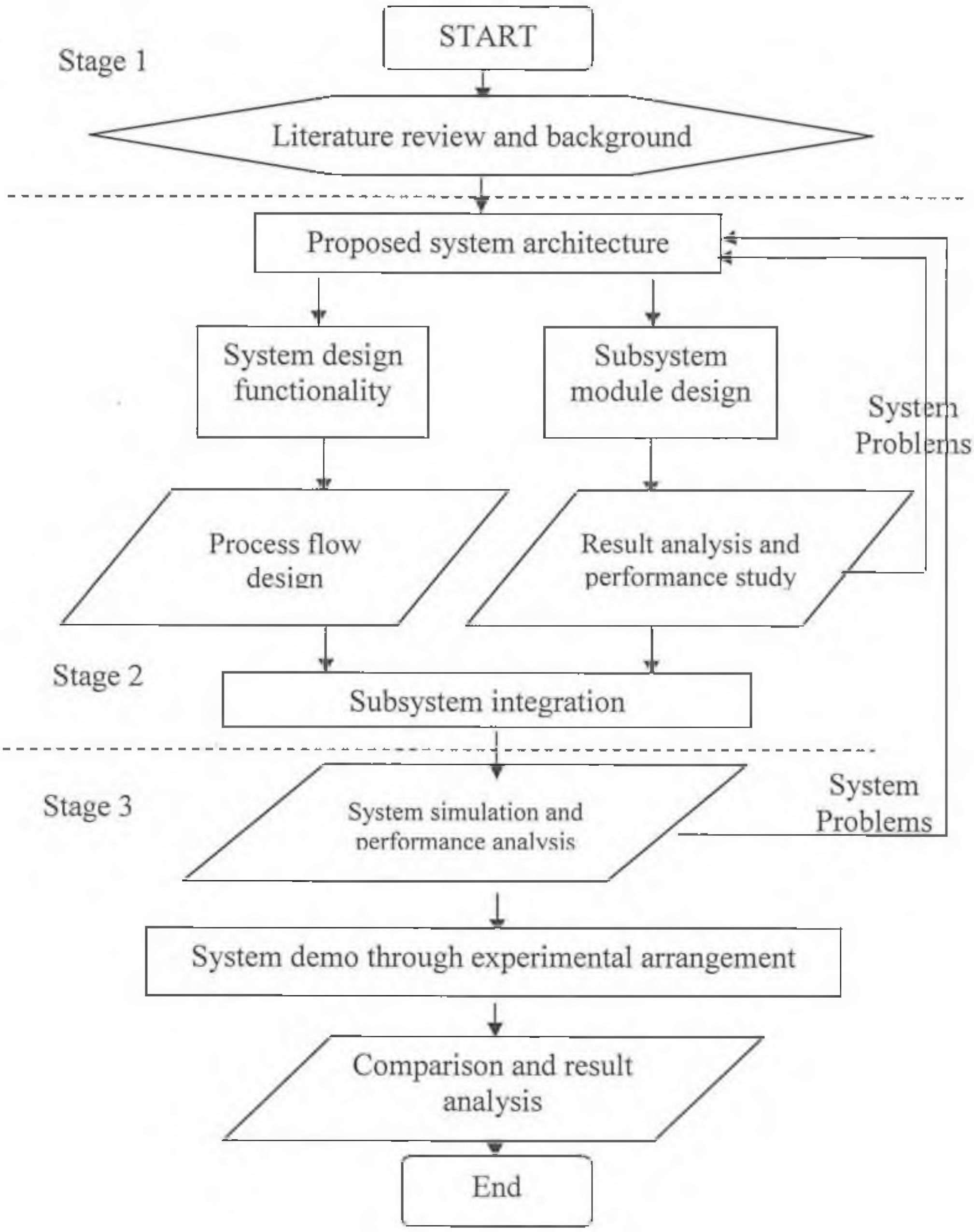

Figure 1.2 Flow chart of the research methodology

This work is basically divided into three main stages, and each stage addresses all the issues encountered in completing this research. This flow-chart shows the development of the system and covers all the issues that have to be considered throughout this project. At the initial stage, investigation on the current research and technology of selection in NG-PON2 system is conducted. This involves studying the literature on TWDM PON system as well as all the related research works. It is important to study and comprehend the concept of TWDM PON system to support future requirement of PON system. This stage also covers the investigation on the architecture of the enhanced TWDM PON, which is called flexible TWDM PON system, to support more users with more dynamic and flexible design architecture. In this literature, the system architecture is differentiated from the previous works proposed by the other research institutions including the university, telecommunication vendors, and telecommunication providers. In the second stage, the proposed AOPR TWDM PON system architecture with different flexibility is designed. In this stage, the proposed design focuses on developing AOPR OLT module to support packet routing and packet multicasting and broadcasting. This phase provides the detail about the design scenario and event trace flow of both flexible functions. In this stage, the proposed AOPR TWDM PON system architecture is also designed. This architecture consists of subsystem of OLT, ONO, and ODN systems. In OLT system, a new module, called AOPR OLT module, is designed to integrate with semiconductor optical amplifier (SOA), multi-wavelength PPS, and cyclic arrayed waveguide grating (AWG). The main components involved in supporting the proposed design such as SOA and AWG will be discussed.

The third stage is the system characterization and performance study. In this stage, the best correlation between OLT PON port transmitting power and multiple wavelength PPS to support packet routing and packet multicasting and broadcasting is obtained. Each component is characterized and each parameter is obtained to get the best performance to support the proposed system. Using the (VPIphotonics) simulation result as a reference design, each of the subsystem of OLT, AOPR and ONU, and ODN will be constructed. Each subsystem has a different design and parameter, and results of simulation performance and experimental characterization are compared. Using subsystem characterization result as a reference, each subsystem is integrated for a complete end-to-end system testing. Result analysis is the last phase in this study. This phase provides results to support the physical layer performance study. Physical performance of the system is measured by analyzing the quality of signal through bit-error rate (BER) optical signal-to-noise ratio and ONU-received sensitivity. This stage is the most crucial stage because it is where the entire study is analyzed thoroughly. It is important to get the best input parameter setup so that an optimum design can be determined. In addition, should there be any problems or limitations on the design, it will then be rectified and further implications, suggestions, and possible recommendations will be given.

1.7 Thesis Outline

In Chapter 1, an overview of the research, aims, motivation, problems, and reasoning of the study are discussed. The objectives of the research work are also presented accordingly. Methodology of the research work that covers the matters in completing the work is thoroughly discussed.

Chapter 2 broadens the discussion and provides more detailed background and reviews of the optical access technology focusing on PON system technology. Each PON evolution will be reviewed and the requirements to support future PON are identified. Technology selection to support NG-PON2 is reviewed and studied based on its pros and cons. As proposed by FSAN and ITU-T standardization, TWDM PON technology has been selected by most of the major telecommunication companies and vendors for deployment in NG-PON2. In this study, the enhanced TWDM PON system (called flexible TWDM PON system), which was proposed to support more users and more flexible in allocating bandwidth to all users in all ODN links, gains the main focus in the literature. In this chapter, the development of the AOPR TWDM PON system is also proposed and each of the main module and components to support the proposed architecture will be discussed in detail.

In Chapter 3, system design of the proposed architecture to support different functions in AOPR TWDM PON system is elaborated, with algorithm of each function proposed and discussed. The chapter focuses at the first and second flexible functions, which are flexible packet routing and flexible multicast and broadcasting functions. This chapter also presents the developments of subsystem module to support AOPR OLT. The characterization of SOA as main components to support AOPR used in XGM module is studied in detail. The design of multi-wavelength pump probe signal module is proposed to reduce the wavelength tuning delay in the system by using high-speed wavelength select switch PPS design and Always ON design. The performance of the fundamental method used in each sub module design is assessed using simulation design and the effect of performance parameter on each of the input parameter is measured.

Chapter 4 presents the simulation setup and performance study of the proposed AOPR TWDM PON system. On the basis of the subsystem reference result in Chapter 3, the overall performance of the proposed architecture is measured; each of submodules will be integrated and BER performance to support maximum total link loss and ONU-received sensitivity is measured. To achieve the research objective of supporting high-power budget to enhance the number of users and area of system coverage, system optimization and signal amplification are introduce in AOPR OLT module design. All these activities are measured using commercial VPI simulation tools.

Chapter 5 presents the development of AOPR OLT module in the proposed system; design consideration and experimental setup. The effect of different input power from two input signals on the performance of the model is also highlighted. Later, the performance of wavelength-tuning-free design module using fixed type of wavelength in OLT transmitter to support both WSS and All ON method is discussed and compared with the conventional method using TLS to support wavelength conversion. Also, the development of high-performance AOPR TWDM PON system is presented by integrating each sub module such as OLT AOPR, multiple ODN link, and ONU module. This model acts as a whole proposed system that emulates functions in AOPR TWDM PON system. The physical performance studies such as BER, optical signal-to-noise ratio, and ONU-received sensitivity of the system are also obtained. Finally, analysis results based on the simulation and measurement are compared, discussed, and concluded.

Finally, in Chapter 6, concluding remarks and recommendations for future prospects for this work are given and the original contributions are highlighted.

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