SPECTRALLY EFFICIENT AND LOW COST TIME AND WAVELENGTH DIVISION MULTIPLEXED PASSIVE OPTICAL NETWORK SYSTEMS

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I dedicate this dissertation

To my parents and family….

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My PhD journey is a challenging, enjoyable, and has a lot of inspiration that pushed me to learn, grow in order to set my sights high. I would like to express my heartfelt gratitude for all the people who accompanied me to reach this point.

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ABSTRACT

The next-generation passive optical network stage 2 (NG-PON2) intends to support stacking 10 Gb/s wavelengths and maintaining the compatibility with the deployed legacy passive optical network (PON) systems. Essentially, Time and Wavelength Division Multiplexed-PON (TWDM-PON) is the best solution for NG-PON2 that aims to support a symmetric 40 Gb/s data rate transmission, a split ratio of 1:64 and a distance up to 60 km. Unfortunately, most of the existing low cost and practical TWDM-PON solutions are still incapable to support remote users and inefficient for spectral bandwidth in higher services. Typically, low cost transceivers are avoided as they suffer from significant frequency chirp that seriously impact its transmission performance at the bit rate above 10 Gb/s. Therefore, the objectives of this thesis are to improve the current TWDM-PON power budget in supporting more access services reaching the remote customers to enhance the bandwidth capacity at lower cost and to reduce the complexity implementation problem. This is achieved by overcoming the significant frequency chirp of the low cost transceivers used such as reflective semiconductor optical amplifier (RSOA) and directly modulated lasers (DMLs), which are suitable for high data rate transmission. The RSOA chirp is mitigated using a single bi-pass delay interferometer (DI) at the optical line terminal (OLT) while the DML chirp is managed by ensuring its resulting current is in phase with the bandwidth enhancement factor, α , at both optical network unit (ONU) and OLT. Apart from that, DML equipped with dispersion compensation fiber (DCF) technique for power budget improvement is also proposed. Furthermore, low cost schemes for even higher data rate TWDM-PON up to 56 Gb/s is proposed utilizing highly spectral efficient 16-quadrature amplitude modulation (16-QAM). The results are obtained from physical layer simulation, Optisystem$^{\text{Trademark}}$ and Matlab$^{\text{Trademark}}$, where relevant significant parts are verified through theoretical analysis. The simulation results demonstrate a sufficient dispersion compensation with a record of 56.6 dB power bughet for DML-based TWDM-PON transmission system. While results are not absolute due to variations that can occur in practical implementation, analysis demonstrates the feasibility of the proposed methods.

ABSTRAK

Generasi seterusnya rangkaian pasif optik peringkat kedua (NG-PON2) berhasrat untuk menyokong panjang gelombang tindan 10 Gb/s dan mengekalkan keserasian dengan sistem rangkaian pasif optik (PON) sedia ada. Pada asasnya, pemultipleksan masa dan panjang gelombang PON (TWDM-PON) adalah penyelesaian terbaik NG-PON2 bertujuan untuk menyokong penghantaran data 40 Gb/s secara simetri, nisbah pecahan 1:64 dan jarak capaian sehingga 60 km. Malangnya, kebanyakan penyelesaian TWDM-PON berkos rendah dan praktikal masih tidak mampu untuk menyokong pengguna terpencil dan penggunaan jalur lebar spektrum yang tidak cekap bagi perkhidmatan lebih tinggi. Biasanya, penghantar-penerima berkos rendah dielakkan kerana isu '*frequency chirp*' yang serius dan sangat mempengaruhi prestasi penghantarannya pada kadar lebih tinggi daripada 10 Gb/s. Justeru itu, objektif-objektif tesis ini adalah untuk meningkatkan peruntukan kuasa TWDM-PON semasa bagi menyokong lebih capaian perkhidmatan bagi pelanggan terpencil, meningkatkan kapasiti jalur lebar dengan kos lebih rendah dan pengurangan masalah kerumitan perlaksanaan. Ini dicapai dengan mengatasi isu '*frequency chirp*' yang signifikan bagi penghantar-penerima hulu berkos rendah seperti penguat reflektif semikonduktor optik (RSOA) dan laser termodulat secara langsung (DMLs) untuk penghantaran kadar data yang tinggi. '*Chirp*' RSOA diatasi menggunakan sebuah interferometer lengah (DI) dwi-lulus pada terminal talian optik (OLT) manakala '*Chirp*' DML diuruskan dengan memastikan fasa arusnya adalah sepadan dengan faktor pengembangan jalur lebar, α, di kedua-dua unit rangkaian optik (ONU) dan OLT. Selain itu, DML yang dilengkapi dengan teknik fiber pampasan penyerakan (DCF) bagi peningkatan peruntukan kuasa juga dicadangkan. Tambahan pula, skim-skim berkos rendah untuk kadar data TWDM-PON yang lebih tinggi sehingga 56 Gb/s dicadangkan menggunakan spektrum berkecekapan tinggi 16-pemodulation amplitud kuadratur (16-QAM). Hasil keputusan diperolehi daripada simulasi lapisan fizikal, Optisystem$^{\text{Trademark}}$ dan Matlab$^{\text{Trademark}}$ dengan bahagian-bahagian penting yang berkaitan disahkan melalui analisis teori. Hasil keputusan simulasi menunjukkan pampasan penyerakan yang mencukupi dengan rekod 56.6 dB bughet kuasa untuk sistem penghantaran TWDM-PON berasaskan DML. Walaupun hasilnya tidak mutlak kerana variasi yang boleh berlaku dalam pelaksanaan secara praktikal, analisis kami menunjukkan kebolehlaksanaan kaedah-kaedah yang dicadangkan.

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LIST OF ABBREVIATIONS

ASE	-	Amplified Spontaneous Emission
AWR	-	Arrayed Waveguide Router
APD	-	Avalanche Photodiode
AWG	-	Arrayed Waveguide Grating
A/D	-	Analog to Digital
BER	-	Bit Error Rate
BPF	-	Band Pass Filter
BTB	-	Back to Back
CDR	-	Data Recovery
DP-MZM	-	Dual Parallel Mach Zehnder Modulator
DI	-	Delay Interferometer
DCF	-	Dispersion Compensation Fiber
DML	-	Directly Modulated Laser
DAM	-	Dual-Arm Modulator
Dmux	-	Demultiplexer
DSP	-	Digital Signal Processing
D/A	-	Digital To Analog
DFB-LD	-	Distributed Feedback Laser Diode
DSB	-	Double Side Band
EML	-	Electro-absorption Modulated Laser
EDFA	-	Erbium Doped Fiber Amplifier
EDC	-	Electronic Dispersion Compensation
FSAN	-	Full-Service Access Network
FTTx	-	Fiber-To-The-x

FTTH	-	Fiber-To-The-Home
FTTC	-	Fiber-To-The-Curb
FTTB	-	Fiber-To-The-Building
FP-LD	-	Fabry Perot-Laser Diode
FSR	-	Free Spectrum Range
FEC	-	Forward Error Correction
GPON	-	Gigabit Passive Optical Network
GEPON	-	Gigabit Ethernet Passive Optical Network
Gb/s	-	Gigabit/second
HD	-	High Definition
ICT	-	Information and Communication Technology
ITU-T	-	International Telecommunication Union-Telecommunications
IEEE	-	Institute of Electrical and Electronics Engineers
LLU	-	Local Loop Unbundling
Mb/s	-	Megabit/second
Mux	-	Multiplexer
MAI	-	Multiple Access Interference
NG	-	Next Generation
NRZ	-	Non-Return-To-Zero
OLT	-	Optical Line Terminal
ONU	-	Optical Network Unit
ODN	-	Optical Distribution Network
OSA	-	Optical Spectrum Analyzer
OOK	-	On-Off-Keying
OPEX	-	Operational Expenditure
OFDM-PON	-	Orthogonal Frequency Division Multiplexing-Passive Optical Network
OCDM-PON	-	Optical Code Division Multiplexing-Passive Optical Network
OCS	-	Optical Carrier Suppression
P2MP	-	Physical Point-To-Multi-Point
PON	-	Passive Optical Network

PRBS	-	Pseudorandom Binary Sequence
PIN	-	Positive Intrinsic Negative
QAM	-	Quadrature Amplitude Modulation
RN	-	Remote Node
RSOA	-	Reflective Semiconductor Optical Amplifier
RoF	-	Radio over Fiber
RX	-	Receiver
RF	-	Radio Frequency
SNI	-	Service Node Interface
SMF	-	Single Mode Fiber
SSB	-	Single Sideband
SOA	-	Semiconductor Optical Amplifier
SBS	-	Stimulated Brillouin Scattering
SPM	-	Self-Phase Modulation
TDMA	-	Time Division Multiplexing Access
TDM-PON	-	Time Division Multiplexing- Passive Optical Network
TECL	-	Tunable External Cavity Laser
TOF	-	Tunable Optical Filter
TX	-	Transmitter
TFF	-	Thin-Film Filter
TWDM-PON	-	Time and Wavelength Division Multiplexed-Passive Optical Network
TIA	-	Trans-impedance Amplifier
UNI	-	User Network Interface
VCSEL	-	Vertical Cavity Surface Emitting Laser
WDM-PON	-	Wavelength Division Multiplexing- Passive Optical Network
WBF	-	Wavelength Blocking Filter

LIST OF SYMBOLS

$E_{in}(t)$	-	DML Complex Output
ω_o	-	Angular Frequency of DML Optical Source
$I_{in}(t)$	-	Intensity Modulation Signal
P_o	-	DML Output Power at a Certain Time
m_{IM}	-	Intensity Modulation Index
ω	-	Angular Modulation Frequency
φ_{IM}	-	Phase Associated with the Intensity Modulation
$P_{in}(t)$	-	Output Power to Intensity Modulation Signal $I_{in}(t)$
A_o	-	Mean Amplitude of the Signal
m_{AM}	-	Amplitude Modulation Index
$\Phi_{in}(t)$	-	Phase Modulation
m_{PM}	-	Phase Modulation Index
φ_{PM}	-	The initial Phase Associated to $\Phi_{in}(t)$.
$N(t)$	-	DML Carrier Density
$S(t)$	-	DML Photon Density
$\exists$	-	Confinement Factor
N_o	-	Carrier Density at Transparency
τ_p	-	photon lifetimes
τ_e	-	electron lifetimes
r_{sp}	-	Fraction of Spontaneous Emission
q	-	Electron Charge
V	-	Active Layer Volume
ε	-	Gain Compression
γ_o	-	Differential Quantum Efficiency
g_o	-	Gain Slope Constant
R_{sp}	-	Carrier Recombination Rate

A	-	Non-radiative Recombination Rate
B	-	Radiative Recombination Coefficient
C	-	Auger Recombination Coefficient
v_g	-	Group Velocity
a_o	-	Active Layer Gain Coefficient
I_{th}	-	Construction Industry Directory
N_{th}	-	Decision Support System
ϕ	-	Multiple Criteria Decision Making
$\Delta F(t)$	-	Common building Structural Systems
α	-	Bandwidth Enhancement Factor
κ	-	Adiabatic Chirp Coefficient
$h\upsilon$	-	photon energy
$P(t)$	-	DML output power
t_s	-	Turn on Delay
N_{initi}	-	Initial Carrier Density
I	-	Total Injection Current
I_{initi}	-	threshold current
I_{th}	-	Threshold Current
I_b	-	Bias Current
I_m	-	Modulation Current
$\Delta B_{3-dBDML}$	-	3-dB Bandwidth of DML
G	-	DML damping Rate Ratio of the Gain
f_r	-	Relaxation oscillation frequency
$H_\omega(\omega)$	-	Amplitude Frequency Response
ω_r	-	Angular Modulation of Relaxation Oscillation Frequency
i	-	Common building Structural Systems
EVM	-	Common building Structural Systems
$X_{tx,n}$	-	transmitted symbol of the constellation associated with the n_{th} symbol
$X_{rx,n}$	-	received symbol associated with $X_{tx,n}$
M	-	Symbols for the in-phase quadrature constellation
$X_{tx,\max}$	-	Field Vector of the outermost constellation point
$X_{tx,y}$	-	Ideal Transmitted Field Vector

f	-	Modulation Frequency
n	-	Modulation Format

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CHAPTER 1

INTRODUCTION

1.1 Background

The incessant growth of converged broadband access network service and the increasing demands for multimedia applications have led to a notable and sustained development and adaptation in information and communication technology (ICT). For instance, multimedia applications such as video on demand (3D video and super HD), cloud computing, social network, peer to peer file sharing and online gaming are the main bandwidth driver's in future broadband convergence services [1-3]. Hence, the incessant rise of bandwidth demand in broadband access networks in both industry and academia is a challenge that requires intensive innovations to be satisfactorily met.

This demand for bandwidth, to some-extent, can be met by moving the optical fiber deeper to the access network segment towards the subscribers and new applications demanding deeper fiber architectures such as mobile backhaul/front-haul backhauling wireless networks [4]. For access segment and in view of supporting this demand, networks such as Fiber-To-The-x(FTTx) have been increasingly deployed in various parts of the world. There are different types of FTTx networks such as FTTH (home), FTTC (curb) and FTTB (building) that offer direct fiber connection to or close to the home [5, 6]. Since FTTx network implementations are based on a physical point-to-multi-point (P2MP) topology, it is a favorable solution that FTTx is implemented based on passive optical networks (PONs) technology. To be more economically viable by offering high bandwidth to subscribers and to gain low energy consumption per bit based on PONs access technologies, efforts are being made to overcome the hurdles of the pending common carriers such as bandwidth scarcity, capacity and cost efficient implementations. The PON technology has a P2MP topology with no active elements in the signal's path which connects optical line terminal (OLT) with several optical network units (ONUs) at the customer sites through one or more 1: N optical splitter based optical distribution network (ODN) [7, 8]. Figure 1.1 shows a general architecture of PON.

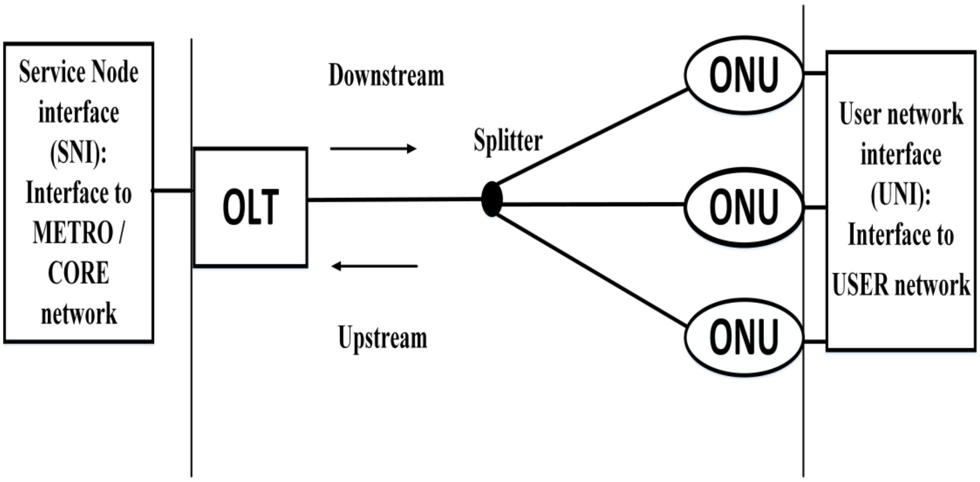

Figure 1.1 PON Architecture.

In order to provide broadband access services, different cost effective implementations of pertinent types of PON technologies have been standardized. The most common PON technologies are Gigabit PON (GPON) and Gigabit Ethernet PON (GE-PON) standards. GPON is mainly deployed in North America and Europe while the deployment of GE-PON is more common in East Asia. GPON standard was commercially specified based on ITU-T G.984 while GE-PON was standardized by IEEE working group 802.3ah [9]. The state of the art of PON technologies are based on time division multiplexing (TDM)/time division multiplexing access (TDMA) transmission mechanisms. The data rate capability of GPON standard is 2.5 Gb/s for the downstream transmission direction and 1.25 for the upstream transmission direction. As for GE-PON, the data rate capability is 1.25 Gb/s for the downstream and upstream directions. However, the bandwidth spectrum is shared by all subscribers in the system where a subscriber can only get access to several Mb/s [9-11].

In spite of the progress that has been made by GPON and GE-PON, the passive splitter loss based on ODN presents a hurdle to support higher user date rate, an increased number of users and longer reach. At the same time, emerging applications such as Ultra HD videos will continue to push bandwidth demands further. However, multimedia applications continue to proliferate where the current PON bandwidth scarcity is unable to meet demands for new applications of broadband converged services. Hence, it presents a challenge for the current PON systems to keep pace with the ever increasing demands for higher bandwidth and the migration of legacy PON systems for future converged services. This represents an inadequate contribution that warrants meeting new future broadband access network requirements [12]. Therefore, network operators decided that next-generation-PONs (NG-PONs) deployment was obliged to satisfy the following requirements: (1) larger split ratio,(2) greater maximum reach than the current GE-PON/GPON architectures, (3) support higher bandwidth for business, residential, and back hauling services, (4) support backward compatibility, (5) allow coexistence with the current PONs systems, and (6) lower cost implementation [13,14]. As a result, the first stage of next-generation called NG-PON1 or 10 Gb/s PON systems was standardized with two bodies of NG-PON1 defined by both IEEE and ITU-T. In view of adhering to future bandwidth growth over existing ODNs after GPON and GE-PON, trials of 10 Gb/s solution (in both downstream and upstream directions), namely IEEE Std. 802.3av 10 GE-PON and ITU-T XG-PONs, were defined by IEEE and the ITU-T with FSAN group [14-16].

Even though the NG-PON1 (10 Gb/s systems) brought good effort and progressive upgrades have been made for optical access network, it is still not sufficient to meet the requirements of new broadband optical access network. In addition, network operators continue to see extraordinary growth of traffic carried over their networks for more services accommodation. Trials beyond 10 Gb/s classes systems must fulfill major requirements for new broadband access network. These requirements are; (1) simultaneous support of legacy, new and mobile backhaul services, (2) maximum reuse of existing ODN and achievement of minimum service interruption to the subscribers that do not migrate, (3) flexibility, reliability, efficiency and scalability in both bandwidth and power consumption, (4) larger split ratio and reach than the previously deployed 10 Gb/s systems, and (5) cost effective implementation, (6) higher performance transmission, (7) resiliency and (8) security optimization [17]. In order to keep pace with the above needs of new and future broadband access network, the second stage passive optical network (NG-PON2) beyond 10 Gb/s was initiated in 2010 [17,18]. The physical media dependent (PMD) layer recommendation (ITU-T G.989.2) was conducted by members of the FSAN and ITU-T Study Group 15, Question 2 groups. NG-PON2 architecture standard is aimed to support 40 Gb/s as a multiple wavelength bidirectional system and compatible with power split ODN with a concern of high priority for industry application [18-20]. There are several access technologies that can potentially satisfy the above criteria which can be grouped into beyond 10 Gb/s trials. Such technologies include 40 Gb/s TDM-PON, wavelength division multiplexing PON (WDM-PON), time and wavelength division multiplexing-PON (TWDM-PON), orthogonal frequency division multiplexed PON (OFDM-PON) and optical code division multiplexed-PON (OCDM-PON) [21-23]. Figure 1.2 shows the trends on PON standardization roadmap based on technological deployment.

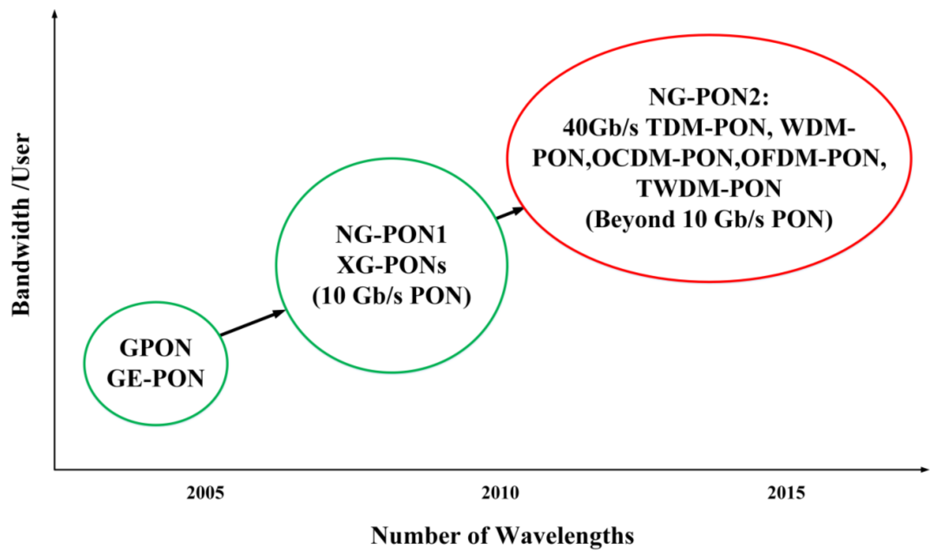

Figure 1.2 Trends of PONs standardization roadmap

After intensive studies of the above beyond 10 Gb/s PON technologies, TWDM-PON was selected to be a pragmatic solution in both industry and academia aspects for NG-PON2 by FSAN group of telecomm companies members. The rest of the NG-PON2 or beyond 10 Gb/s PON technologies, such as WDM-PON and OFDM-PON, are believed to be less suitable due to high immaturity, high cost sensitivity and no adherence to the ODN backward compatibility [23, 24]. The TWDM-PON system is identified in FSAN as their best opportunity to support 40 Gb/s via stack multiple wavelengths and appears to be compatible with power split ODN that meets the NG-PON2 requirements. It also satisfies the requirements of operational expenditure (OPEX) involved in running their networks and this drives an aim to keep inventory to a minimum [25]. TWDM-PON system is also highly mature to be scalable, flexible, reliable and efficient in both bandwidth and power consumption [26, 27].

1.2 Motivation

The tremendous contribution and expansion of the deployable standard access networks and systems is still in progress. This is simply due to the continuous increase of bandwidth demand powered by industry and academia innovation. In response to that, the full service access network (FSAN) group has been using the roadmap shown in Figure.1.2 to guide the development of passive optical networking (PON) standards beyond GPON (gigabit PON). The FSAN roadmap shows two generations of PON beyond GPON: so-called the next-generation PON (NG-PON) 1 and 2, respectively. Although this roadmap figure is fairly simple, it conveys several key guiding principles that have served to steer the development of ITU-T PON standards and systems. The goal for practitioners and researchers of PON technologies is to enhance the capacity in a single fiber. It has been clear that the history tells us that a successful next-generation PON is one with increased capacity per user while maintaining low cost per user. Thus, the goal of the PON researcher is to come up with ideas that improve the performance with a clear low cost path. Good performance at low cost is preferable to great performance at high cost.

The recent trend of PON technologies is TWDM-PON which has been nominated as the current NG-PON2 technology. The TWDM-PON supports 40 Gb/s data transmission through four XG-PONs that are stacked using four pairs of wavelengths. For simpler network deployment and inventory management purposes, the ONUs aimed to use colorless tunable transmitters and receivers. Ideally, the transmitter is tunable to any of the upstream wavelengths while the receiver can tune to any of the downstream ones. In order to achieve a power budget, optical amplifiers are employed at the OLT side to boost the downstream signals as well as to pre-amplify the upstream signals. ODN remains passive since both the optical amplifier and WDM Mux/DeMux are placed at the OLT side.

While most of TWDM-PON components are commercially available, it is interesting for technology planners or system operators (researchers or practitioners) to overcome the hurdles of TWDM-PON system such as bandwidth scarcity, capacity and cost effective implementations. Most of the existing works, based on performance evaluation of the TWDM-PON, are concerned with physical layer aspects. In this thesis, several key enabling technologies to improve the state of art of TWDM-PON system has been explored and presented. The advantages of the pure TWDM-PON system are its ability to facilitate symmetric applications and its flexibility in future scaling of bandwidth, power budget, cost implementation. Therefore, the technical choices and challenges are analyzed in terms of bandwidth, power budget, data rate transmission, cost and feasibility.

1.3 Problem Statement

The current challenge in a bidirectional TWDM-PON system specification based on fiber communication technology is that they are less efficient in terms of bandwidth and cost implementation. Most of the existing low cost and practical TWDM-PON solutions are still incapable to support remote users and to support efficient spectral bandwidth for higher services. For example, reflective semiconductor optical amplifier (RSOA) and direct modulated lasers (DMLs) have a serious chirp issue that can degrade the transmission performance as the modulation bandwidth is limited by the carrier lifetime in the active layer and typically ranges between 2 to 3.5 GHz. Therefore, it is challenging to accommodate high speed data rate signals with this severely limited band device. Hence, optical equalization is required in this system to mitigate the distortions induced by chirp and compensate for signal deterioration. In addition and in contrast to existing improvement of power budget, there is still great demand for TWDM-PON access systems with improved link budgets that can offer services to more customers to more remote areas effectively. Here, high splitting ratio and long reach TWDM-PON system require investigation. More data rate transmission on TWDM-PON system requires more wavelengths that lead to increase cost and complexity. Thus, to cope with further increase capacity in an efficient manner, spectral efficient techniques are needed for a more scalable and efficient TWDM-PON system.

1.4 Research Objectives

The main objective of this thesis is to foster and propose solutions for TWDM-PON system that are efficient in terms of bandwidth and cost implementation. This can be achieved by the following sub-objectives.

1- To design and implement an efficient TWDM-PON system with high spectral techniques.

2- To improve the power budget of 40 Gb/s TWDM-PON system based DMLs through DCF dispersion compensation technique.

3- To enhance the bandwidth transmission of a low cost RSOA using delay interferometer (DI) for 40 Gb/s TWDM-PON system.

1.5 Research Scope

The scope of this research is covering work in the following aspects.

- TWDM-PON architecture and key enabling technologies for the state of the art of TWDM-PON for NG-PON2 technology.
- Key application of TWDM-PON architecture.
  - ✓ Optical line terminal (OLT): Non-return-to-zero-on-off-keying (NRZ-OOK) modulation format, 16 quadrature amplitude modulation (QAM) modulation format, Pseudorandom binary sequence (PRBS), absorption modulated laser (EML), directly modulated laser (DML), erbium-doped fiber amplifier (EDFA), delay interferometer (DI), semiconductor optical amplifier (SOA), optical spectrum analyzer (OSA), WDM multiplexer (Mux), WDM demultiplexer (DeMux), dispersion compensation fiber (DCF), circulators and avalanche photodiode (APD) receiver.
  - ✓ Optical distribution network (ODN): Single mode fiber (SMF), Splitter/Combiner device.
  - ✓ Optical network unit (ONU): Non-return-to-zero-on-off-keying (NRZ-OOK), pseudorandom binary sequence (PRBS), directly modulated laser (DML), semiconductor optical amplifier (SOA), optical spectrum analyzer (OSA), tunable optical filter (TOF) and Avalanche photodiode (APD) receiver.

1.6 Research Methodology

In order to achieve the objective of this research, the following method of work will be done into subsections of methods:

1.6.1 DML Simulation

In order to achieve the DML simulation of this research, the following method of work will be done as shown in Figure 1.3:

- A literature review on related topics such as state of the art of direct modulation laser (DML) and the characterization of the chirp of DML.
- Choose the suitable parameters of chirp for reasonable designed less chirped DML, such as bandwidth enhancement factor, adiabatic chirp and the bias current of DML.
- Simulation and analysis of DML based on the selected chirp reduction paprameters.
- The performance evaluation of DML at 10 Gb/s transmission.
- Implement four stacked wavelength TWDM-PON system based on the enhanced DML performance transmission.

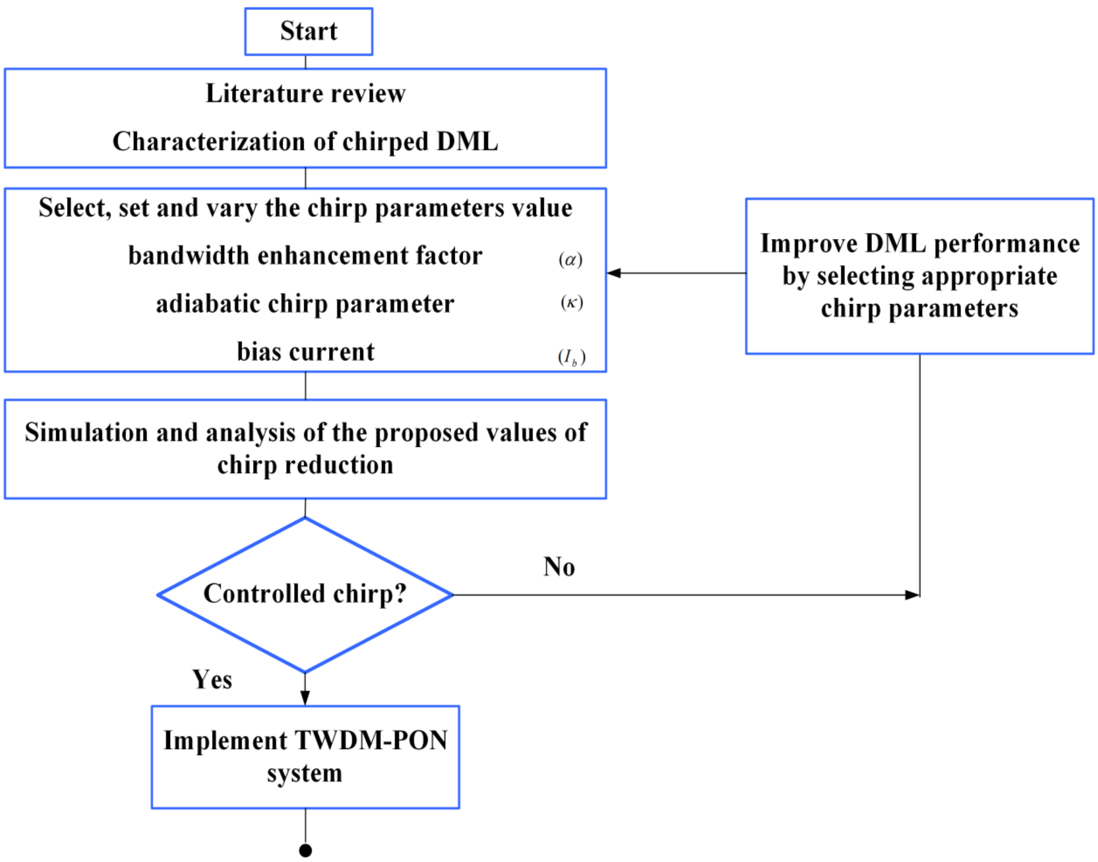

Figure 1.3 Flow chart of DML simulation

1.6.2 RSOA Simulation

In order to achieve the RSOA simulation of this research, the following method of work will be done as illustrated in Figure 1.4:

- A literature review on related topics such as state of the art of direct modulation laser (DML) and the characterization of the chirp of DML.
- Choose the suitable parameters of chirp for a reasonable designe of less chirped DML, such as bandwidth enhancement factor, adiabatic chirp and the bias current of DML.
- Simulation and analysis of DML based on the selected chirp reduction paprameters.
- The performance evaluation of DML at 10 Gb/s transmission.
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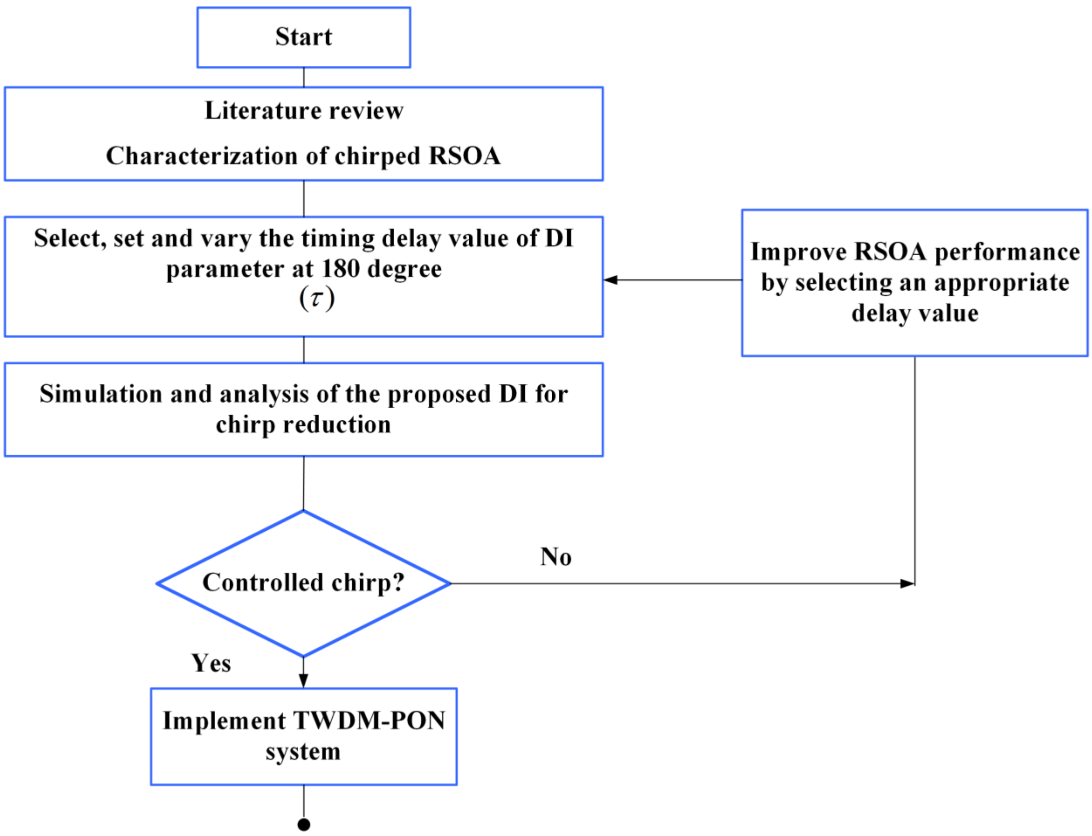

Figure 1.4 Flow chart of RSOA simulation

1.6.3 TWDM-PON Simulation

In order to achieve TWDM-PON system simulation of this research, the following method of work will be done through the following steps as shown in Figure 1.5.

- A comprehensive review on related works of direct modulation laser (DML) based on TWDM-PON state of the art configuration system.
- Implement and design a 10 Gb/s DML TWDM-PON for improved capacity, power budget and bandwidth with different techniques such as 16 QAM, DCF and DI.
- Simulation and analysis of the proposed TWDM-PON.
- The performance evaluation of the proposed TWDM-PON transmission at bit error rate (BER) of 10^{-5} and 10^{-6} at optical transmission, electrical eye diagram and proposed schemes feasibility.
- The superiority of the new TWDM-PON system is verified by comparing its performance against related techniques used in literature.

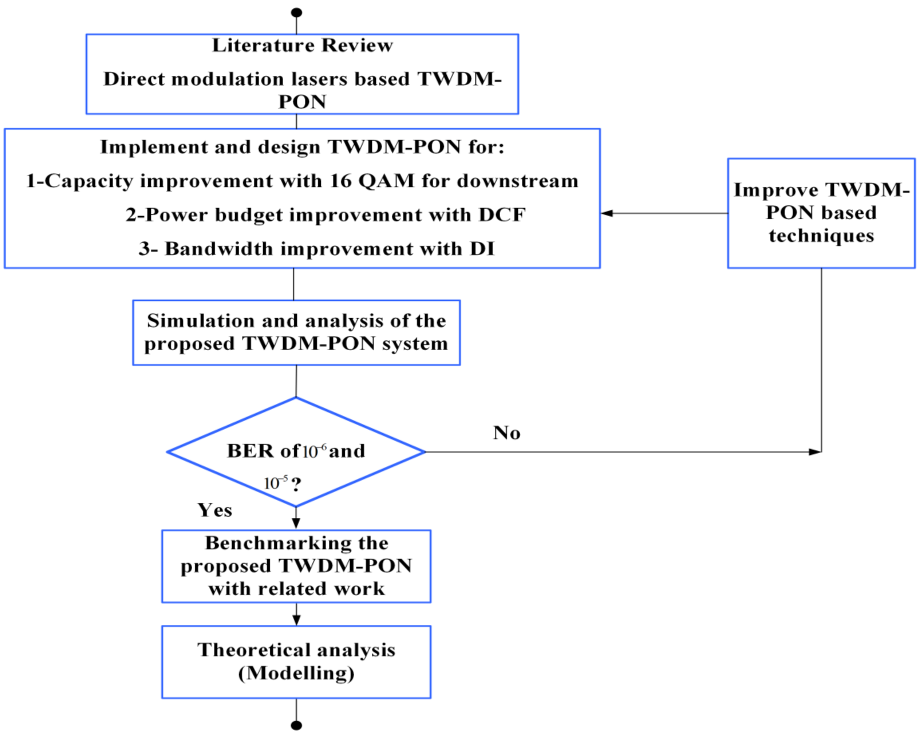

Figure 1.5 Flow chart of TWDM-PON system simulation

1.6.4 Theortical approach

The theortical approach of this research is achieved through the following method as shown in Figure 1.6:

- An intensive study to find the suitable and accurate model for DML and RSOA transmitters, exact wavelength of DCF and SMF, DI and power bughet equations.
- Propose and set parameter values of the above aspects equation (step 1) that similar to the simulated parameter values.
- Calculation and analysis of the equation paprameter values.
- Compare the calculated and simulated results.
- The results are validated.

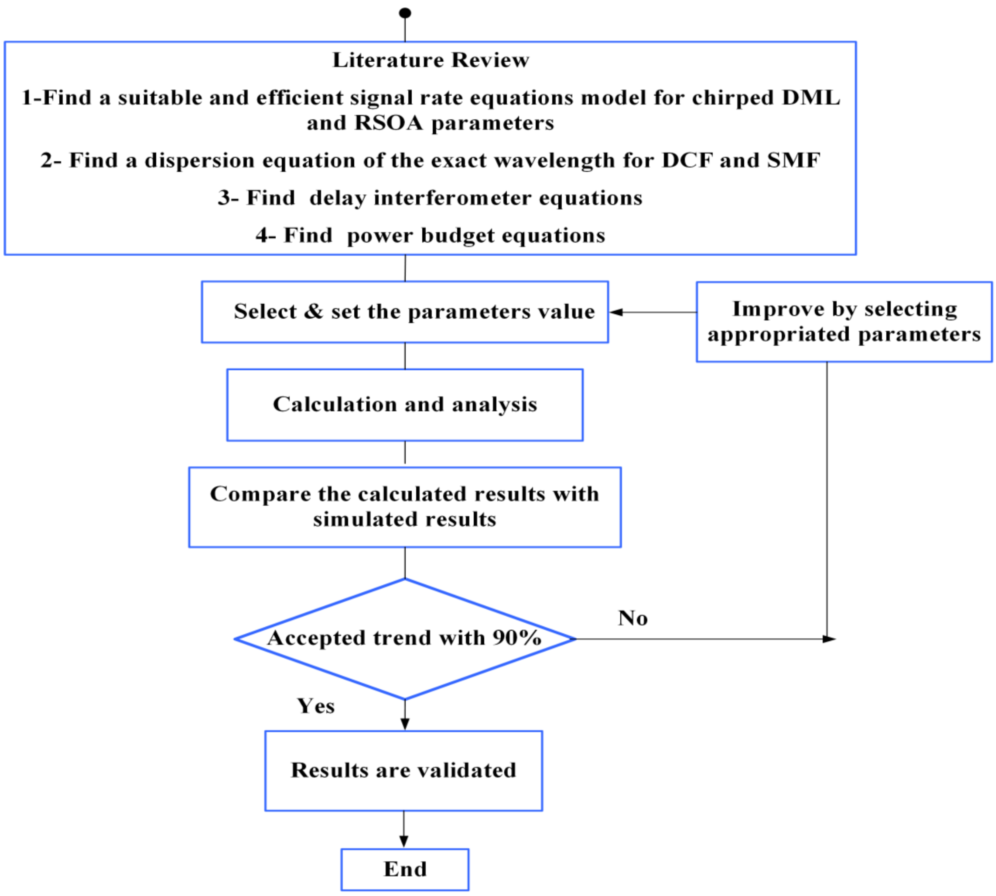

Figure 1.6 Flow chart of theortical approach

1.7 Thesis Contribution

This thesis presents significant contributions which mainly fall on TWDM-PON architecture. It is worth noting that the simulations of the development on TWDM-PON architecture proposed in this thesis are performed using Optisystem software. In addition, MATLAB software is a powerful for modelling calculations design system. Finally, mathematical formulas to support the chirp model and validation are presented. A brief description on this thesis contribution is illustrated in the following subsections.

- The design of a new, efficient and low cost TWDM-PON system that aims to improve the capacity to 56 Gb/s for downstream and with 128 users over 40 km single mode fiber (SMF) reach. The proposed TWDM-PON system utilizes the highly spectral efficient 16 quadrature amplitude modulation (QAM) with a 20 GHz radio frequency signal distribution using single sideband signal (SSB) that is generated by an optical dual-arm modulator (DAM) for each wavelength to support 14 Gb/s. Compared to the existing techniques, the design presents an impressive improvement in terms of the capacity of TWDM-PON system.
- The design of a new technique that employs chirped DML for upstream link each wavelength without dispersion technique utilization at optical network unit (ONU) of TWDM-PON system to improve the capacity to 40 Gb/s. The chirp of DML is minimized by output waveform such as output power (bias current that was assumed to be 75 mA and above the threshold current), and bandwidth enhancement factor. The feasibility of DML is verified in-terms of bandwidth enhancement factor, extinction ratio and launched input power.
- Development of a symmetric 40 Gb/s TWDM-PON system based on DML transmission that utilizes dispersion compensation fiber (DCF) technique for an efficient power budget. The findings reveal that a good performance quality with less than 2 dB dispersion penalty can be achieved over 140 km standard single mode fiber (SMF). As a result, a system power budget of 56.6 dB and more than 512 users with 140 km purely passive reach is achieved.

- The feasibility is verified in terms of dispersion compensation, power budget with dispersion and bandwidth enhancement factor. Its performance is compared against the other schemes used in literature in terms of power budget TWDM-PON system. The proposed scheme is an asset of TWDM-PON technology and its implementation complexity is minimal to a level that is comparable to the existing commercialized systems with a cost that is sufficiently low to meet the cost constraints of the access networks (Chapter 4).
- Development of a new 40 Gb/s TWDM-PON system which incorporates low cost and chirped reflective semiconductor optical amplifier (RSOA) for both downstream and upstream directions is designed based on a delay interferometer (DI). A successful transmission of the proposed work study where an aggregate capacity of 40 Gb/s is transported over 40 km transmission distance with 32 splits.
- A single bi-pass DI with 40 GHz free spectrum range (FSR) deployed in the optical line terminal (OLT) is used to enhance the poor bandwidth performance of the RSOA due to frequency chirp. The feasibility is verified in-terms of 40 GHz free spectrum range (FSR) DI. This scheme is benchmarked by comparing its performance against the other schemes used in literature in terms of low cost ONU implementation, simplicity and the data rate based on RSOA TWDM-PON system. (Chapter 5).
- Theoretical and Simulation analysis of the chirp, output power, bandwidth enhancement factor, power budget, dispersion, FSR of DI and frequency response is presented for the purpose of this thesis validation.

1.8 Thesis organization

A detailed description of our research undertaken to achieve the objectives is presented in this section. Each of the following paragraphs explains the contents of each chapter.

Chapter 1 provides a general introduction to PON access networks and the motivation behind TWDM-PON system. This chapter also introduces the problem statement of this research, objectives, research scope and the research methodology of the proposed schemes on TWDM-PON is illustrated. Finally, the thesis contributions and organization are outlined.

Chapter 2 discusses the literature review part which will define the important concepts of this research. Key enabling technologies for next generation passive optical networks second stage (NG-PON2) are presented and compared in this chapter. Then architecture of TWDM-PON and its remarkable features are presented. Finally, this chapter covers the different TWDM-PON schemes and the important findings of previous studies which are most related to this work.

Chapter 3 intends to improve the TWDM-PON system capacity in a scalable, efficient and cost-effective manner. A simple and cost effective scheme to improve highly spectral efficient 16 quadrature amplitude modulation (QAM) with 20 GHz Radio over fiber (RoF) is presented to improve the capacity of downstream link signal. Two critical performance parameters of DML are investigated to mitigate the chirp frequency of DMLs in upstream link. This results in a successful transmission of 56 Gb/s downstream and 40 Gb/s upstream bandwidth. The BER performance of four wavelengths of downstream and upstream directions is evaluated. Moreover, the effect of the DML nonlinearity is studied for high power transmission. In this chapter, the results are compared with the performance of previous schemes of TWDM-PON system in terms of data rate accommodation, low cost and simplicity of implementation.

Chapter 4 is dedicated to improve the power budget of a symmetric 40 Gb/s TWDM-PON system that utilizes a dispersion compensation fiber (DCF) technique. In this chapter, the performances of directly modulated laser (DML) and electro absorption modulated laser (EML) in the downstream direction under high launched power is compared. The BER performance and power budget for one and four wavelengths for both is evaluated. The feasibility of DCF techniques to compensate positively accumulated dispersions from different transmission fiber distances is presented. The performances and improvements of the proposed 40 Gb/s TWDM-PON is benchmarked with previous TWDM-PON schemes in terms of achieved ODN power budget.

Chapter 5 presents the architecture of the a symmetric 40 Gb/s TWDM-PON based on transmission of low cost reflective semiconductor optical amplifier (RSOA) for both downstream and upstream directions. The drawback of the low cost RSOA is the low frequency chirp to accommodate high data rate transmission. To overcome this shortfall, a single bi-pass delay interferometer (DI), deployed in the optical line terminal (OLT), is proposed to enhance the poor performance of the RSOA with respect to the low bandwidth induced by laser chirp. The performance of four wavelengths of downstream and upstream directions is evaluated. Different line rates for RSOA transmission for downstream and upstream links are presented. The performance of the proposed scheme is verified by comparing it with previous schemes of TWDM-PON system in terms of data rate accommodation, low cost implementation of lasers such as a tunable external cavity laser (T-ECL) and dual parallel Mach Zehnder modulator (DP-MZM).

Chapter 6 summarizes the research outcomes and concludes the thesis. A few schemes for future research are also proposed and discussed.

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