QOS-AWARE BANDWIDTH ALLOCATION ALGORITHM FOR LONG RANGE PASSIVE BROADBAND ACCESS NETWORK

SITI HASUNAH BINTI MOHAMMAD

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DEDICATION

To my mother and father, who taught me that, no matter how difficult the journey, everything will be beautiful in the end.

To my husband, who always reminded me to put first things first.

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ABSTRACT

Next generation broadband access networks are gaining more interest from many key players in this field. The demands for more extended reach and higher bandwidth are among the driving factors for such a network. The advantages of this network include a wider coverage area reaching 100 km, even beyond; increased bandwidth capacity and transmission speed, but with low cost and energy consumption. One promising candidate is the Long Reach Passive Optical Network (LR-PON). LR-PON is a term that refers to the consolidation of the metro and the access networks in the traditional PON, which also means the merger of the multiple Optical Line Terminals (OLTs) and the Central Offices (CO) in the network. LR-PON can simplify the network by reducing the number of network elements, equipment interfaces, and even nodes which significantly reduces the network's Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Although the LR-PON can provide extended reach, this results in increased propagation delay of Dynamic Bandwidth Allocation (DBA) messages exchanged between the OLT and Optical Network Units (ONUs), leading to degradation of DBA and Quality of Service (QoS) support. Longer round-trip-time (RTT) in LR-PON causes redundancy in the DBA mechanism as the ONU polling cycle becomes smaller than RTT. Therefore, this thesis focuses on deploying an efficient QoS-aware bandwidth allocation algorithm with an appropriate Service Interval (SI) setup for LR-PON to ensure the delay is maintained under ITU-T G.987.1 standard requirement, named as Service Interval-based Bandwidth Algorithm (SIBA). OMNeT++ software is used to run a discrete event simulation of the network. Simulation findings reveal SIBA's superior performance for all the traffic classes where the mean upstream delays of Transmission Container (T-CONT) 2 and T-CONT 3 improved up to 88% and 85% respectively, compared to Immediate Allocation Colourless Grant (IACG) algorithm. SIBA also surpasses the mean upstream delay of the Efficient Bandwidth Utilization (EBU) algorithm by up to 90% for both T-CONT 2 and T-CONT 3, and by 83% for T-CONT 4 compared to the Comprehensive Bandwidth Allocation algorithm for LR XG-PON (CBA-LR) .

ABSTRAK

Rangkaian capaian jalur lebar generasi hadapan semakin menarik perhatian para penyelidik dalam bidang ini. Permintaan rangkaian dengan jangkauan yang lebih panjang dan lebar jalur yang lebih tinggi adalah antara faktor pendorong. Antara kelebihan rangkaian ini adalah kawasan liputan yang lebih luas mencecah lebih 100 km, kapasiti lebar jalur dan kelajuan penghantaran yang tinggi dengan kos dan penggunaan tenaga yang rendah. Salah satu teknologi berpotensi ialah rangkaian optik pasif jangkauan panjang (LR-PON). LR-PON merujuk kepada penyatuan metro dan rangkaian akses dalam rangkaian optik pasif (PON) tradisional, justeru penyatuan sejumlah pangkalan talian optik (OLT) dan pejabat pusat (CO) di dalam rangkaian. LR-PON berupaya meringkaskan rangkaian dengan mengurangkan bilangan elemen, kelengkapan antara muka, dan juga nod, sekaligus mengurangkan perbelanjaan modal (CAPEX) dan perbelanjaan operasi (OPEX). Namun, kelewatan perambatan pertukaran mesej peruntukan jalur lebar dinamik (DBA) antara OLT dan unit rangkaian optik (ONU) boleh meningkat dan membawa kepada kemerosotan sokongan DBA dan kualiti perkhidmatan (QoS). Masa perjalanan pergi balik (RTT) yang lebih lama dalam LR-PON menyebabkan lelebihan dalam mekanisme DBA kerana kitar tinjauan ONU yang lebih kecil daripada RTT. Oleh itu, tesis ini memfokuskan penggunaan algoritma peruntukan lebar jalur sedar QoS yang cekap dengan selang perkhidmatan (SI) yang sesuai untuk LR-PON bagi memastikan kelewatan dikekalkan di bawah keperluan standard ITU-T G.987.1, dinamakan sebagai peruntukan jalur lebar berasaskan selang perkhidmatan (SIBA). Perisian OMNeT++ digunakan untuk menjalankan simulasi rangkaian secara diskret. Keputusan simulasi mendedahkan prestasi unggul SIBA untuk semua kelas trafik di mana kelewatan hulu min kontena penghantaran (T-CONT) 2 dan T-CONT 3 masing-masing diperbaiki sehingga 88% dan 85%, berbanding algoritma geran tanpa warna peruntukan terdekat (IACG). SIBA juga melepasi kelewatan hulu min bagi algoritma penggunaan jalur lebar cekap (EBU) sehingga 90% untuk kedua-dua T-CONT 2 dan T-CONT 3, dan sebanyak 83% untuk T-CONT 4 berbanding algoritma peruntukan jalur lebar komprehensif untuk LR XG-PON (CBA-LR).

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LIST OF ABBREVIATIONS

LR	-	Long Reach
PON	-	Passive Optical Network
LR-PON	-	Long Reach Passive Optical Network
OLT	-	Optical Line Terminal
CO	-	Central Office
CAPEX	-	Capital Expenditure
OPEX	-	Operational Expenditure
DBA	-	Dynamic Bandwidth Allocation
OLT	-	Optical Network Unit
QoS	-	Quality of Service
RTT	-	Round-Trip-Time
SI	-	Service Interval
FSAN	-	Full Service Access Network
ITU-T	-	International Telecommunication Union
E-PON	-	Ethernet PON
G-PON	-	Gigabit Passive Optical Network
XG-PON	-	10G-PON
IEEE	-	Institute of Electrical and Electronics Engineer
RE	-	Reach Extender
ODN	-	Optical Distribution Network
FTTH	-	Fiber-to-the-Home
TDM	-	Time-Division-Multiplexing
SBA	-	Static Bandwidth Allocation
VoIP	-	Voice over Internet Protocol
GIANT	-	GigaPON access network
IACG	-	Immediate Allocation Colourless Grant
EBU	-	Efficient Bandwidth Utilization
SDH	-	Synchronous Digital Hierarchy

MAC	-	Medium Access Control
SIBA	-	Service Interval-based Bandwidth Allocation
CAGR	-	Compound Annual Growth Rate
NG-PON	-	Next Generation Passive Optical Network
NG-PON1	-	Next Generation Passive Optical Network stage 1
NG-PON2	-	Next Generation Passive Optical Network stage 2
WDM	-	Wavelength Division Multiplexing
OFDM	-	Orthogonal Frequency Division Multiplexing
DP-MQAM	-	Dual Polarization Quadrature Amplitude Modulation
DP-MQPSK	-	Dual Polarization Modulation Quadrature Phase-Shift Keying
DSP	-	Digital Signal Processing
SPM	-	Self-Phase Modulation
XPM	-	Cross-Phase Modulation
FWM	-	Four Wave Mixing
ACTS	-	Advanced Communications Technologies and Services
PLANET	-	Photonic Local Access NETwork
SuperPON	-	Super Passive Optical Network
DWDM	-	Dense Wavelength-Division Multiplexing
OEO	-	Optical-Electrical-Optical
BER	-	Bit Error Rate
WC-PON	-	Wavelength Converting Passive Optical Network
PIEMAN	-	Photonic Integrated Extended Metro and Access Network
EDFA	-	Erbium Doped Fiber Amplifier
SOA	-	Semiconductor Optical Amplifier
DRA	-	Distributed Raman Amplification
SLA	-	Service Level Agreements
SR	-	Status Reporting
NSR	-	Non Status Reporting
T-CONTs	-	Transmission Containers
TS-DMB	-	Two-State Dynamic Minimum Bandwidth
LR G-PON	-	Long Reach Gigabit-PON
NA+	-	Newly Arrived Frames Plus
PCG-OSFI	-	Predictive Colorless Grants - Offset-based Scheduling with

		Flexible Intervals
BwUpdate	-	Bandwidth Update Algorithm
ABRT	-	Assured Bandwidth Restoration Times
IPACT	-	Centralized Interleaved Polling Algorithm
GREAL	-	G-PON Redundancy Eraser Algorithm for Long Reach
CBA-LR	-	Comprehensive Polling and Scheduling Mechanism for LR XG-PON
OMCI	-	ONU Management and Control Interface
MIB	-	Management Information Base
OMCC	-	ONU Management and Control Channel
PLOAM	-	Physical Layer OAM Operations, Administrations and Maintenance
SDU	-	Service Data Unit
GTC	-	G-PON Transmission Convergence
PDU	-	Protocol Data Unit
GEM	-	G-PON Encapsulation Method
PCBd	-	Physical Control Block Downstream
BIP	-	Bit-Interleaved Parity
Plend	-	Payload Length Indicator
BWmap	-	Upstream Bandwidth Map
Alloc-ID	-	Allocation Identifier
PLO	-	Physical Layer Overhead
PLOu	-	Physical Layer Overhead upstream
PLOAMu	-	Physical Layer OAM Operations, Administrations and Maintenance upstream
DBRu	-	Dynamic Bandwidth Report upstream
SDI	-	Successive Data Interval
AB	-	Allocation Byte
PIR	-	Peak Information Rate
GIR	-	Guaranteed Information Rate
PBS	-	Peak Burst Size
VB	-	Allocated Bandwidth
PLI	-	Payload Length Indicator

PTI	-	Payload Type Indicator
HEC	-	Header Error Control
CIR	-	Committed Information Rate
FB	-	Frame Bytes
GPA	-	Guaranteed Phase Allocation
UBW	-	Unutilized Bandwidth
SPA	-	Surplus Phase Allocation
RUB	-	Remaining Unassigned Bandwidth
SRI	-	Static Report Inconsistency
OMNeT++	-	Objective Modular Network Testbed in C++

LIST OF SYMBOLS

AB_{min}	-	Minimum allocation bytes
AB_{sur}	-	Surplus allocation bytes
SI_{max}	-	Maximum polling period
SI_{max}	-	Minimum polling period
T_{Idle}	-	ONU idle time
$T_{Queuing}$	-	ONU queuing time
T_{ONU}	-	The sum of ONU processing and equalization delay at the ONU
T_{OLT}	-	The grant sending delay at OLT
T_E	-	The equalization delay at the ONU
T_{POLL}	-	The time grants sent to ONUs
$T_{DBA\_Process}$	-	DBA processing time
D_{US}	-	Upstream delay
T_{DBA_Cyle}	-	DBA cycle time
λ	-	Traffic arrival rate
μ	-	Upstream service rate
D_m	-	Maximum access delay
T_p	-	The fixed propagation time required for the DBRu field to reach the OLT
T_{pr}	-	The time required for the transmission and decoding of the messages in each node
j	-	OLT number in the network = 0, 1, 2,…, n
i	-	ONU number in the network = 0, 1, 2,…, 15
FB	-	Total frame bytes
k	-	Traffic class for T-CONT = 2, 3, 4
R_0^k	-	T-CONT(k) queue report of ONU(i)
P_0	-	ONU processing time = 35us
β_{OLT}	-	Unit of computational complexity for each Gate and Report

		messages in OLT
β_{ONU}	-	Unit of computational complexity for each Gate and Report messages in ONU
β_{Total}^{DBA}	-	Total computational complexity
Th	-	Throughput in a time cycle
$W_{Total}^{Received}$	-	Total receive windows
W_{Total}^{Trans}	-	Total transmitted windows
$W_{th,i}^{Received}$	-	The received window from a thread of ONU *i*
$W_{th,i}^{Trans}$	-	The transmitted window from a thread of ONU *i*

CHAPTER 1

INTRODUCTION

1.1 Background

Entering the zettabytes era, the subscribers are demanding for higher and longer coverage of internet, as far as possible. Since decades, fiber optical network has been providing the best service to the end users involving urban and rural areas. Fiber optical network, specifically Passive Optical Network (PON) is widely known as the last mile solution due to its high bandwidth, long reach, low power consumption, easier deployment and upgradation (1–5). It is reflected by the standards introduced by the full service access network (FSAN) group of International Telecommunication Union (ITU-T) which cover PON solutions operating at gigabit rates, especially G-PONs (6,7). PON is named based on the fact that it functions only using passive elements in the distribution network (8–11). Thus, the network can minimize the operating and maintenance costs of the access network with the absent of active element.

Ethernet PON (E-PON) and Gigabit PON (G-PON) are the main contributors in PON technology, standardized by Institute of Electrical and Electronics Engineer (IEEE) and ITU-T respectively. Among these two systems, G-PON surpasses E-PON in terms of capacity, scalability and splitter ratio. EPON offers bit rate up to 1 Gbps, while G-PON serves bit rate up to 2.4 Gbps for downstream transmission. E-PON supports fiber split ratio up to 16 users, while G-PON supports up to 64 split ratios which is much higher than E-PON. This is due to the application of Reach Extender (RE) by G-PON at the Optical Distribution Network (ODN). The use of RE can increase the power budget and in the same time, increase the reach and the split ratio (3). In term of cost, G-PON cannot beat E-PON as it requires tighter physical of the transport components due to its complexity, but G-PON has the best support of all the PONs for heterogeneous networking (12).

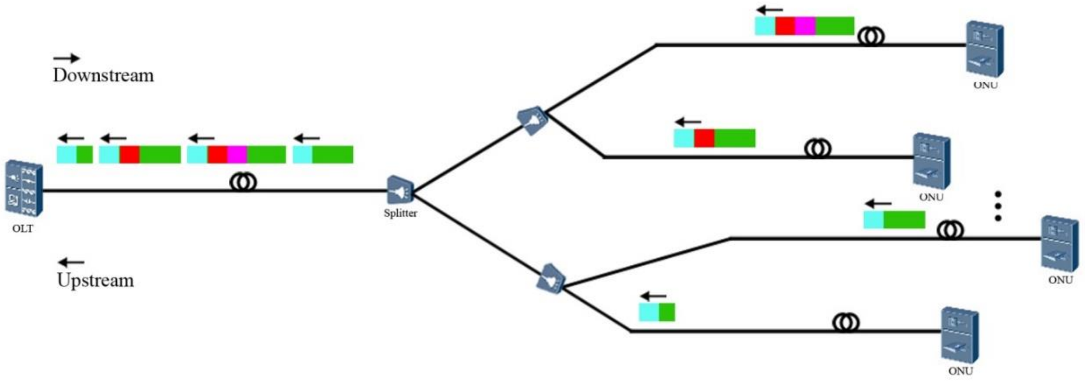

Figure 1.1 TDM operation concept in upstream transmission of G-PON.

G-PON has become an excellent candidate for Fiber-to-the-Home (FTTH) access networks because of its high quality of services (QoS). In the downstream operation, G-PON is a point-to-multipoint network in which data is broadcast to all Optical Network Units (ONUs) while in the upstream transmission; each ONU will have to send the data in time-division-multiplexing (TDM) manner (as shown in Figure 1.1). To control the upstream bandwidth transmission between ONUs, a bandwidth allocation algorithm is used in the Optical Line Terminal (OLT) so that the collision of the data between ONUs can be avoided.

According to literatures (1,3,6,7,9,13–21), there are two main methods of bandwidth allocation in G-PON, which are static bandwidth allocation (SBA) and dynamic bandwidth allocation (DBA). SBA is a TDM-like allocation where each ONU gets its predefined bandwidth allocation whether it uses it or not. This method is suitable for network which requires constant bandwidth allocation such as voice over Internet Protocol (VoIP) or TDM. If there is no congestion occurs in the transmission and the total required upstream bandwidth is less than 1.24 Gbps, the upstream channel available bandwidth is sufficient to service all ONUs with virtually no queuing. The unused bandwidth of certain ONUs could be utilized by other ONUs to offer high speed connections and better upstream QoS to the end users. The DBA mechanism is required to fulfil this objective.

Since decades, many G-PON DBA algorithms have been proposed, but there were only a few works on G-PON FSAN-compliant DBA algorithms which have been physically implemented, named as GigaPON access network (GIANT), Immediate Allocation Colourless Grant (IACG) and Efficient Bandwidth Utilization (EBU) algorithms. GIANT (6) is the first physically implemented DBA algorithm which introduced a down counter for bandwidth allocation. The OLT can assign bandwidth to a queue only when the down counter of the queue has expired. GIANT is indeed simple and feasible, but it causes higher delay since a request of a queue cannot be granted until the down counter expired. This degrades the overall performance of a G-PON system.

Then, the author of (19) introduced IACG where each queue has an available byte counter in addition of a down counter. The available byte counter with positive value allows the OLT to immediately allocate a bandwidth to a queue without having to wait for the down counter to expire. The available byte counter is decreased by the grant amount and recharged when its down counter has expired. It was proven that IACG surpasses GIANT in (6), but on the contrary of its good performance, it does not effectively utilize the unused bandwidth of queues. The unused bandwidth of a queue cannot be used by other starving queues. It is necessary that the unused bandwidth is utilized by queues whose request sizes are greater than their reserved service bandwidth.

Thus, EBU is introduced in (22) to efficiently overcome the unallocated bandwidth problem of IACG. Similar to IACG, every queue has an available byte counter and a down counter. The minor change is: the available byte counter can be negative in EBU. Furthermore, at the end of scheduling, the unused remainder of the available byte counter is added to the negative available byte counters. EBU is proven to increase the utilization of the unallocated bandwidth compared to IACG.

As the work of DBA grows rapidly, the demand for further coverage yet cost effective network also increases. Here came the efforts to improve the existing system either by modifying the physical layer or the network layer technology. There is a proposal to extend PON towards next generation-PON to get higher bandwidth capacity and to serve larger number of subscribers. Long Reach PON (LR-PON) is one of the next generation-PON technologies which aims to extend the optical access network up to 100 km. LR-PON is a term that refers to the consolidation of the metro and the access networks in the traditional PON (3,9,10,23–27), which also means the consolidation of the multiple OLTs and the Central Offices (CO) where they are located in the network (24), as shown in Figure 1.2.

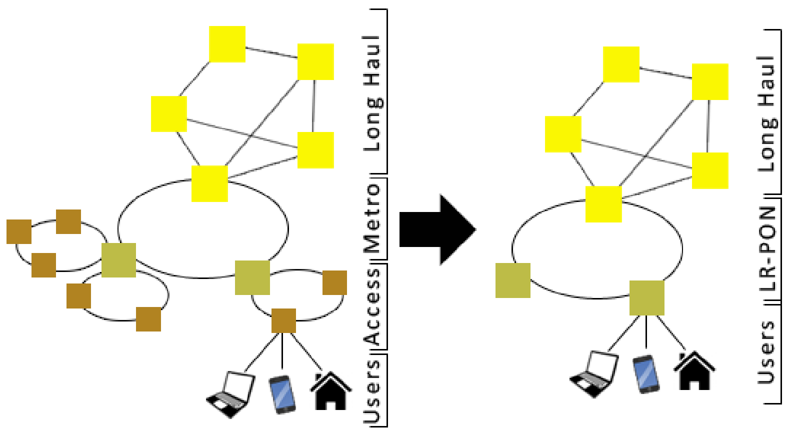

Figure 1.2 Consolidation of the metro and access network in Long Reach PON.

As the metro and access networks can be combined into one extended backhaul fiber, it will be an alternative to more cost-effective solution for the extended reach optical access network. The longer reach also can cover larger splitter size, which results in increasing number of components shared between all subscribers. Cost savings are established as the synchronous digital hierarchy (SDH) rings are replaced with a single backhaul fiber. The local exchange site can be removed as the combined access and metro networks are terminated at the core node to simplify the network, thus giving substantial reduction in overall network costs (27–32).

Many work has been done to address the extension of reach in next generation-PON technologies such as PLANET SuperPON (33), British Telecom LR-PON (34), DWDM-TDM LR-PON (35), LR-WC PON (36), and PIEMAN (37). Following these developed technologies, the researchers are looking deeply into the system as there are pros and cons of the LR-PON technology. Regarding long reach in G-PON, most of the previous work are working with 10G-PON (XG-PON) as it can offer an evolving potential technology to carry multiple services for the first-mile access network (1,14,22,38–43). XG-PON per ITU-T Recommendation G.983.4 (44) provides increased capacity up to 10 Gbps and have been deployed in DBA projects with longer reach beyond traditional 20 km PON. This will be discussed more in Chapter 2.

1.2 Project Contribution

a) To our knowledge, this work is the first attempt to consider service interval (SI) for Long Reach XG-PON beyond 100 km.
b) Delay, frame loss and bandwidth utilization analysis of the proposed bandwidth allocation algorithm for Long Reach XG-PON.
c) Comparative study between existing bandwidth allocation algorithm and proposed bandwidth allocation algorithm.

1.3 Problem Statement

According to Skubic *et al.*, node consolidation of PON is significant in reducing cost and components for the future next generation access networks. However, it is limited by the reach of conventional PON system due to optical power budget constraint to support up to 32 ONUs. To achieve larger degree of node consolidation, extended reach beyond 20 km is needed (3,24,26,35,45–47). In this term, LR-PON is the most suitable and promising technology which can fulfil the criteria needed. Reaching longer coverage and wider subscribers are the main focuses of LR-PON, with fiber distance reaching up to 100 km and beyond.

On the other hand, extending the reach creates serious challenges for medium access control (MAC) layer in LR-PON. As the reach is extended until beyond 100 km, the Round-Trip-Time (RTT) also grows. In PON technology, RTT is the duration in milliseconds (ms) it takes for a network request to go from the OLT to an ONU and back again to the OLT. In a traditional PON, RTT is only 0.1 ms with 10-km span, while in a LR-PON, the RTT is increased to 1 ms with 100 km of OLT-ONU distance, which results in 10x the idle time in a traditional PON (24).

In PON development, DBA is required to prevent collisions, distribute the available bandwidth among the subscribers, and managing QoS (6,48–56), but this mechanism performance relies on the RTT. There will be impact on the delay of the DBA control loop as the reach increases due to an ONU polling cycle or Service Interval (SI) smaller than the RTT (51). The growth of the RTT in LR-PON degrades the system performance, as it causes redundancy of reservation and bandwidth waste due to over-granting (10).

Extended reach results in increased propagation delay of DBA messages exchange between OLT and ONUs (25), which then leads to degradation of DBA and QoS support, plus inefficient utilization of upstream channels. Thus, some modification is needed to improve the existing DBA algorithm to ensure that the algorithm can properly allocate bandwidth to the end users accordingly while minimizing the upstream delays.

Based on the findings and problem as mentioned above, the following are research gap:

a) The existing G-PON FSAN-compliant DBA algorithms do not consider the longer reach beyond the traditional 20 km fiber distance, while the existing LR-PON DBA algorithms either neglect the impact of SI value on network performance e.g. mean delay, throughput, loss, and bandwidth utilization, or assume it to be perfectly working regardless the distance.
b) Most of the existing DBA algorithms focused on high priority traffic class with little support for low priority traffic class, the unutilized bandwidth of currently deployed PON leads to bandwidth wastage, whereas it can be necessarily shared among all traffic classes.

1.4 Objectives of Project

The main objective of this project is to enhance the QoS-aware network transmission in a LR-PON network. Therefore, in achieving this goal, the project is conducted with the objectives stated below:

a) To evaluate the performance of bandwidth allocation algorithms for QoS over LR-PON in terms of upstream delay, throughput, frame loss and bandwidth utilization.
b) To propose new Service Interval-based Allocation Algorithm (SIBA) with improved performance for LR-PON.

1.5 Scope of Work

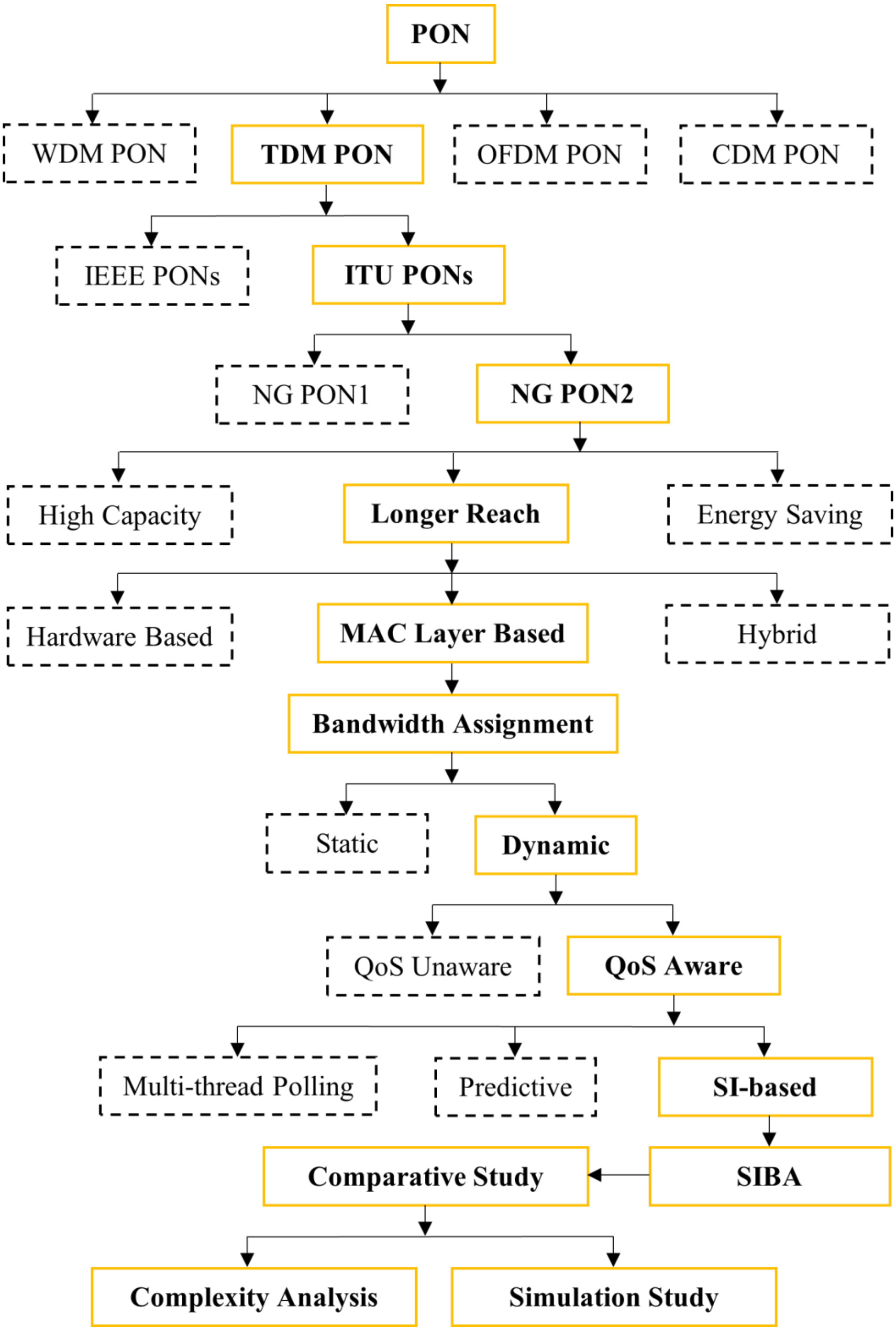

Figure 1.3 Scope of work.

The purpose of this research work is to investigate the possibilities of improvements in the existing bandwidth allocation algorithms for long reach next generation PON, so that the mean delay, frame loss and bandwidth utilization parameters can be optimized. Figure 1.3 shows the scope of work to be carried out in this study. We started with a broader literature review on PON. Currently, the deployed PON network is TDM based. Other alternative PON option were studied but TDM PON is chosen in this study as it is most economic and commercially popular.

The bandwidth assignment schemes in PON, narrowly down to ITU-T G-PON FSAN-compliant DBA are studied, focusing on extended reach beyond 100 km. In selected XG-PON, the upstream bandwidth is shared between all ONUs using a static bandwidth allocation or dynamic bandwidth allocation. The dynamic bandwidth allocation schemes are focused on as they allocate bandwidth efficiently and fairly among ONUs. We proposed a more reliable and effective QoS-aware bandwidth allocation scheme for long reach ITU PONs while studied the impact of longer distance to DBA scheme. Finally, we presented a Service Interval-based Bandwidth Allocation (SIBA) scheme to support longer reach better than the existing schemes.

1.6 Outline of Thesis

This thesis consists of six chapters. The first chapter discusses about the objectives and scopes of this project ending with a summary of works. Theory and literature reviews that have been done were discussed in Chapter 2. The chapter introduces next generation-PON, LR-PON, QoS for the networks and overview of the bandwidth allocation algorithms.

In Chapter 3, the discussion will be on the proposed scheduling algorithms for the LR-PON. It consists of the methodology used in this study, the network downstream and upstream operation, MAC layer study through LR-PON system, case study on existing DBA algorithms and deep explanation of the proposed bandwidth allocation algorithm.

The simulation setup for OMNeT++ will be presented in Chapter 4, including all the parameters, scenarios and assumptions considered in the simulation. The results and discussions will be presented in Chapter 5. This chapter also involves the effects of multiple scenarios to the network system, in terms of mean delay, frame loss and bandwidth utilization performance.

Finally, Chapter 6 discusses the conclusion of this project, recommendations and future work that can be done to improve the project in the future.

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LIST OF PUBLICATIONS

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Mohammad, Siti Hasunah, Zulkifli, N., & Idrus, S. M. (2021). Dynamic bandwidth allocation algorithm for long reach passive optical network. *Telkomnika (Telecommunication Computing Electronics and Control)*, 19(3), 738–746. **(Indexed by SCOPUS)**

Non-Indexed Conference Proceedings

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