Improving Performance of Optical Access Networks

Chien Aun Chan
B. Eng. (Electrical and Electronic Engineering, Hons.) 2003,
M. Eng. (Telecommunication Engineering) 2004.

A Thesis Submitted to the University of Melbourne
in total fulfilment of the requirements of the
degree of Doctor of Philosophy

January, 2010

National Information and Communication Technology Australia (NICTA)
Department of Electrical and Electronic Engineering,
The University of Melbourne,
VIC 3010,
Australia

To my parents and my wife

Abstract

With rising popularity of the Internet and its applications, residential subscribers are beginning to demand access solutions that are more broadband, capable of supporting media-rich services and are comparable in price to existing voice centric telephone services. Rising demand for more bandwidth combined with the increasing cost-effectiveness of optical fibre communications technologies has made fibre-to-the-home (FTTH) based network architecture a future proof solution for solving the access bandwidth bottleneck. Among many variations of FTTH implementations, the passive optical network (PON), which can provide very high bandwidths to the customers, appears to be the most suitable solution to the access network. Other than offering high bandwidth, a PON system offers a large coverage area, reduced fibre deployment due to its point-to-multipoint architecture, reduced cost of maintenance as the result of passive components in the network and ease of upgrades to higher bit rate or additional wavelengths. PON has many upgrade paths and also standard PON implementations could be further improved to support new features essential for emerging service requirements.

This thesis examines the performance improvement of such PON systems with a specific focus on key research issues such as the availability of independent services provisioning in wavelength division multiplexed PON (WDM-PON), bandwidth distribution efficiency in a time division multiplexed PON (TDM-PON) system for both upstream and downstream transmissions, and cost effective upgrade options for PON to higher bit rate such as 10 Gb/s.

WDM-PON technology has been recognised as one of the most future proof access technology due to its virtual point-to-point (PTP) connection between the service providers and customers. However, the provisioning of independent services such as broadcast video or another such service over this network can be complicated. Therefore, this thesis describes the use of closely separated dual baseband channels generation and separation technique for provisioning such independent services in WDM-PON. This technique uses a single laser and modulator for generation and a periodic passive filter for separation of two closely separated baseband channels.

In contrast to WDM-PON, a single wavelength is shared among all the users in the network for TDM-PON. At the central office, optical line terminal (OLT) transmits frames to all optical network units (ONU) at the customer sites in broadcast format. The ONUs will filter unwanted frames and forward the desired frames to the end users. If local traffic between ONUs exist in the network, this traffic need to go through the OLT and inefficiently use up the downstream and upstream bandwidth. This thesis will address this issue by utilising a repeater based remote node (RN) equipped with active forwarding technique to contain the local traffic within the network and improve the network efficiency.

As the number of users in the network increase, bandwidth shared among all the user will result in a decrease in data rate per user. Therefore, bandwidth intensive services will be available in low quality or even be unavailable at peak usage. The thesis demonstrates the use of RN with active forwarding is able to improve the downstream data rate per users reducing downstream bandwidth bottleneck issue for Ethernet PON (EPON). Simulation of a long reach and high split-ratio EPON is presented to show the feasibility of this scheme.

Due to the point-to-multipoint nature of the TDM-PON, specific timeslot will be allocated to each ONU and the ONU can only transmit data upstream to the OLT at the given timeslot. Therefore, the timeslot assignment technique is essential in providing fair and efficient access system for the customers. With the EPON incorporated RN with active forwarding scheme, this thesis presents a new novel local traffic prediction-based dynamic bandwidth assignment (LT-DBA) algorithm, which can enhance the upstream data rate per user, reduce the latency and frame loss ratio at the ONU compared to standard and fixed service bandwidth assignment techniques.

Most of the TDM-PON technologies are standardised at 1 Gb/s. However, bandwidth intensive applications and services have been driving the need for even higher capacity. The standardisation for 10 Gb/s TDM-PON upgrade has already begun and has been researched intensively. In this thesis, a new approach incorporating active filtering within a RN for upgrading Ethernet PON (EPON) to 10 Gb/s will be discussed and its performance will be evaluated through modelling. This upgrade aims to replace the transceivers between OLT and the RN to 10 Gb/s while keeping the transceivers in all ONUs at 1 Gb/s, which results in lower cost of upgrade while maintaining high data rate per user.

Declaration

This thesis is the result of my own work and, except where acknowledged, includes no material previously published by any other person. I declare that none of the work presented in this thesis has been submitted for any other degree or diploma at any University and that this thesis is less than 100,000 words in length, excluding figures, tables, bibliographies, appendices and footnotes.

…………………………………………………..

Chien Aun Chan

Acknowledgements

I would foremost like to express my utmost gratitude to my supervisors, Prof Ampalavanapillai Nirmalathas and Dr. Manik Attygalle. I am very grateful to Prof Ampalavanapillai Nirmalathas for his continuous support and guidance throughout the Ph.D. candidature. Prof. Nirmalathas was always there to listen and to give advice. His words of encouragement in many aspects in the research field have certainly helped me to become a better person and a professional engineer. I am extremely grateful to Dr. Manik Attygalle for his constant support and guidance throughout my candidature. He taught me how to set a goals and accomplish them persistently. He taught me how to ask questions and express my ideas and he showed me how to approach a research problem in different ways. Without their supervision of my Ph.D. program, I could not have completed this dissertation. I feel fortunate enough to work with them and I would like to thank them very much.

I am very thankful to Dr. Nishaanthan Nadarajah, Dr. Vijay Arya and Dr. Marimuthu Palaniswami for serving in my Ph.D. progress committee. Also, I am very grateful to Dr. An Vu Tran, and Dr. Thomas Chae for many valuable discussions and their continued assistance throughout the Ph.D. candidature. I am very grateful to all other research staff in National ICT Australia (NICTA), for interesting technical discussions and useful advice. I wish to thank Dr. Thisara Jayasinghe, Dr. Masud Bakaul, Dr. Milan Khanal, Dr. Prasanna Gamage and friends Liang, Qi, Yuan, Mary, Jian and Chamil for their friendship and support in general.

A special thanks goes to my parents, Kin Tong Chan and Wu Mei Ling Chan for giving me life in the first place and educating me with aspects from both arts and sciences. Last, but not least, I would like to say thank you to my wife, Ye Tang for giving me unconditional support and encouragement to pursue my dream.

I thank you all very much for reading my thesis.

Table of Contents

Abstract I
Declaration III
Acknowledgements V
Table of Contents VII

CHAPTER 1: Introduction

1.1. Optical Access Network 1
 1.1.2. TDM-PON 3
 1.1.3. WDM-PON 6
1.2. Thesis Outline 9
1.3. Original Contributions 12
1.4. Publications Arising From The Work Completed In This Thesis 15
1.5. References 17

CHAPTER 2: Literature Review

2.1. Introduction 21
2.2. Independent Services Provisioning in WDM-PON 24
 2.2.1. Subcarrier multiplexing technique in WDM-PON 25
2.3. Ethernet Passive Optical Network (EPON) 30
 2.3.1. EPON with the Open Systems Interconnection reference model 30
 2.3.2. Multipoint Control Protocol (MPCP) 32
 2.3.3. Round trip time (RTT) measurement 34
 2.3.4. Logical Topology Emulation (LTE) 35
2.4. Long Reach and High Split-ratio PON 38
2.5. Bandwidth Assignment in EPON 42
 2.5.1. Dynamic bandwidth assignment (DBA) 43
2.6. 10 Gb/s EPON Upgrade 47
2.7. Conclusion 51
2.8. References 52

CHAPTER 3: Independent Services Provisioning in WDM-PON
3.1. Introduction 61
3.2. Independent Services Provisioning in WDM-PON 63
3.2.1. Demonstration of the scheme for provisioning of independent Services in WDM-PON 63
3.3. Results 65
3.3.1. Optical spectra 65
3.3.2. DI frequency response 66
3.3.3. Bit-error-rate analysis 68
3.3.4. Eye diagram analysis 69
3.3.5. CSR analysis 71
3.4. Characteristics of Subcarrier Multiplexing Technique 75
3.5. Conclusion 77
3.6. References 78

CHAPTER 4: EPON Incorporating Active Remote Repeater Node with Layer 2 Forwarding
4.1. Introduction 81
4.2. Local Traffic in IEEE 802.3ah LTE 85
4.3. EPON Incorporating Active RN with Layer Two Forwarding Scheme 88
4.3.1. Background overview on repeater based PON 88
4.3.2. MPCP auto-discovery mode 90
4.3.3. EPON with active RN architecture 92
4.4. Simulation Set-up 97
4.4.1. RN frame loss rate 98
4.5. Simulation and Theoretical Analysis 100
4.5.1. Simulation results 100
4.5.2. Theoretical analysis 104
4.6. Conclusion 110
4.7. References 111

CHAPTER 5: Active RN for Improving Downstream Performance in EPON

5.1. Introduction 113
5.2. Techniques for Realising Long Reach and High Split-ratio EPON 115
5.3. Active RN in Long Reach and High Split-ratio EPON 117
5.4. Simulation Setup 119
5.4.1. Simulation setup for evaluation of downstream bandwidth improvement 119
5.4.2. Simulation setup for evaluation of ONU number improvement 121
5.5. Simulation Results 122
5.5.1. Active RN frame loss rate in large scale EPON 122
5.5.2. Delay improvement for EPON with active RN implementation 123
5.5.3. Improvement in downstream data rate 125
5.5.4. Increasing the number of ONUs for scalability 128
5.6. Theoretical Analysis 131
5.6.1. Improvement of downstream data rate per ONU 131
5.6.2. Improvement in ONU number scalability 134
5.7. Conclusion 138
5.8. References 139

CHAPTER 6: Active RN for Improving Upstream Performance in EPON

6.1. Introduction 141
6.2. Improving Upstream Performance Using Active RN 143
6.3. Local Traffic Prediction-based DBA (LT-DBA) 146
6.3.1. Constructing information on ONU location 149
6.3.2. Collision avoidance at feeder link 151
6.4. Simulation Setup 154
6.5. Simulation Results 156
6.5.1. Average packet delay 156
6.5.2. Average queue size 158
6.5.3. Average packet loss ratio 159

6.5.4. Average upstream data rate 160
6.6. Conclusion 162
6.7. References 163

CHAPTER 7: Evaluation of 10/1 Gb/s EPON Incorporating Active RN
7.1. Introduction 165
7.2. EPON 10 Gb/s Downstream Upgrade 167
7.3. Active RN Design for 10 Gb/s EPON Upgrade 171
7.4. Simulation Results and Discussions 174
7.4.1. RN frame loss rate and buffer size 175
7.4.2. Asymmetric 10G-EPON with active RN architecture 176
7.4.3. Cost-effective 10G-EPON with RN architecture 177
7.5. Conclusion 180
7.6. References 181

CHAPTER 8: Conclusions and Future Works
8.1. Thesis Overview 183
8.2. Directions for Future Work 187
8.2.1. Intra and inter ONU scheduling in EPON with active RN 187
8.2.2. Advanced DBA for differentiated class of service 188
8.2.3. Active filtering and forwarding RN chipset 190
8.2.4. Symmetric 10 Gb/s EPON using active RN 191
8.2.5. Multicast support in 10 Gb/s EPON 191
8.3. Conclusions 193
8.4. References 194

APPENDIX A: Acronyms 195
APPENDIX B: Publications 201

1 Introduction

1.1. Optical Access Network

An access network often refers to the series of wires, cables, and equipments that lay between a customer or a business telephone termination point and the local exchange to provide the communication access for the customers to the outside world. Traditionally, the access network was termed ‘last mile’, which describes the ‘final leg’ delivering connectivity from a telecommunications service provider (SP) to a customer [1, 2]. Due to the increasing demands and importance of access networks to support variety of services, it has been renamed to ‘first mile’, to symbolise its priority [2, 3].

At the early stage, the access network infrastructure consisted of copper twisted-wire pair connecting customers’ telephone sets to local exchange. The telecommunications network was designed to support voice traffic. Digital transmission over such cables was first introduced with the use of trunk level 1 (T1) lines. A T1 line (1.544 Mb/s) carries 24 voice channels from the customers in a 64 kb/s Pulse-Code-Modulation (PCM) format and distribute customers’ data traffic to the central office (CO) [4]. At this juncture, voice traffic dominated the usage of communications networks and plain old telephone system (POTS) was adequate to fulfill customers’ demands.

However, the Internet boom in the 1990s resulted in residential subscribers beginning to demand first mile access solutions that are broadband, offer Internet media-rich services and are comparable in price to existing networks [3]. SPs were looking for techniques, which could provide higher bandwidth services compared to connection oriented dial-up and integrated services digital networks (ISDN). As a result, techniques such as asymmetric digital subscriber line (ADSL), very high speed digital subscriber line (VDSL) and cable modem systems came to be the solutions for the access networks' bottleneck [5, 6]. Though these services provide higher bandwidth; they have transmission distance limitations where available bandwidth decreases as the distance to local exchange increases. Furthermore, DSL and cable modem services appears to be inadequate in the near future with the introduction of even higher intensive bandwidth applications such as Internet Protocol Television (IPTV), video-on-demand (VOD), online gaming services, real time video conferencing, etc.

With the reduction in cost of optical components, service providers found that the optical transmission networks once used for long haul transport can form as a solution for the bandwidth bottleneck in the access network [7]. Consequently, telecommunications carriers have started to deploy fibre transmission links into the access networks that has given the rise to fibre-to-the-curb (FTTC), fibre-to-the-building (FTTB) and fibre-to-the-home (FTTH) or FTTx where 'x' depends on the fibre termination point. Among a number of proposed architectures to provide optical connectivity for FTTx such as point-to-point links, active optical networks (AONs) and passive optical networks (PONs), PONs have been regarded as the most suitable next generation optical access network architecture [8-12]. The PON architecture is a point-to-multipoint system containing a passive power splitter/combiner, which connects multiple users to the Central Office (CO) using standard single mode fibre (SMF). The splitter will split into branches and terminated at the optical network units (ONU) at the customer premises or subscribers' home [3].

A PON can be categorised depending on the transmission technology and data rates used in the system. Time division multiplexed PON (TDM-PON) such as asynchronous transfer mode PON (APON) [13], broadband PON (BPON) [14], gigabit PON (GPON) [15, 16], and Ethernet PON (EPON) [3, 17] share a single wavelength per direction between all ONUs. The single wavelength channel will be time multiplexed into n time slots for n ONUs. Frames inserted into each timeslot will be standard dependent (Ethernet or ATM) and hence, the data rates specified for each standard varies. In contrast with TDM-PON, wavelength division multiplexed PON (WDM-PON) enable separate wavelength channel from the CO to each ONU [18-20]. A passive arrayed waveguide grating (AWG) router situated at the remote node (RN) is used in WDM-PON architecture to route multiple wavelength channels from the input port to the intended output port connected to the individual ONU, which achieves similar function to the passive power splitter/combiner used in TDM-PON.

1.1.2. TDM-PON

An early standardised work on FTTH network architecture was by Full Service Access Network (FSAN) working group formed by major telecommunications service providers and system vendors. Consequently, corporation of FSAN and the International Telecommunications Union (ITU) created a standard on PON based optical access network that uses ATM as its Open System Interconnection (OSI) reference model's layer two protocol [4]. The initial PON architecture was named ATM-PON or APON with a symmetrical 155 Mb/s upstream and downstream bit rates. The specification was amended in year 2001 and was named BPON to allow asymmetrical 155 Mb/s upstream and 622 Mb/s downstream transmissions, as well as symmetrical 622 Mb/s transmissions [1]. Due to the growing traffic volume in the access networks, telecommunication SPs realised that the requirement of an architecture which can support higher bit rates with higher efficiency for data traffic is critical. However, BPON and APON that are based on 53 bytes ATM cell were not suitable to carry Internet protocol (IP) traffic efficiently. To overcome this issue, the ITU introduced a new standard which is named GPON using Generic Framing Procedure (GFP) to improve the efficiency by allowing a mix of variable size frames and ATM cells [1, 15-16].

Prior to the development of GPON standard, Institute of Electrical and Electronics Engineers (IEEE) has developed the EPON through IEEE 802.3ah Ethernet in the First Mile (EFM) task force [17] to address BPON's limitations. EPON is similar to BPON and GPON in terms of point-to-multipoint architecture and TDM/TDMA transmission for downstream/upstream. However, EPON uses Ethernet technology instead of ATM based technology and its cost-effective advantage attracts a lot of interests from telecommunication SPs around the world.

EPON is a PON-based network that carries data traffic encapsulated in Ethernet frames as defined in IEEE 802.3 standard. EPON utilises the existing 802.3 specification, including the use of 802.3 full duplex media access control (MAC) [21]. It uses 8B/10B line coding (8 data bits encoded as 10 line bits) and operates at standard symmetric Ethernet speed of 1 Gb/s [22].

EPON consists of a number of users that are connected to an ONU and *n* ONUs are connected to a single optical line terminal (OLT) via a 1 × *N* splitter/combiner to form the point-to-multipoint transmission system as shown in Fig. 1.1. The figure also presents the EPON downstream transmission. The standardised Ethernet technology is broadcasting by nature. Therefore, it is perfectly suited to EPON architecture where frames are broadcasted by the OLT to every ONU and each ONU extract frames that are not destined to them based on the logical link identity (LLID) [23]. The insertion of frames that are destined to different ONUs is achieved through TDM.

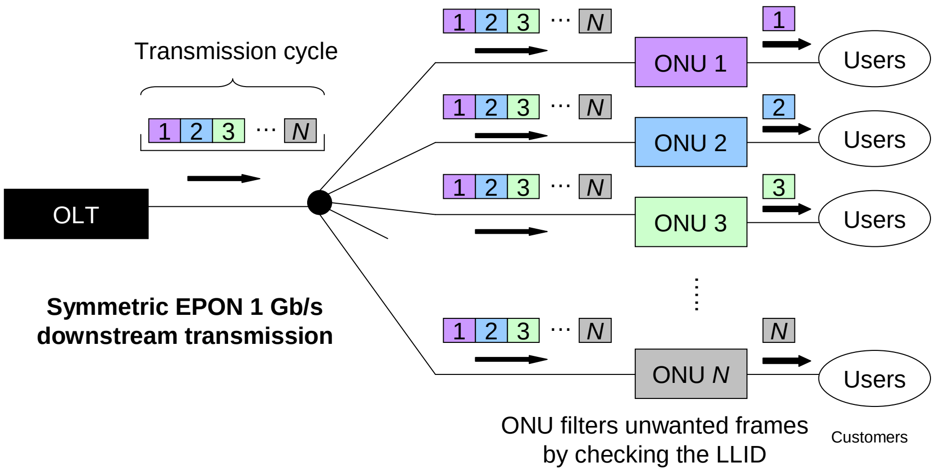

Fig. 1.1: EPON architecture with downstream transmission.

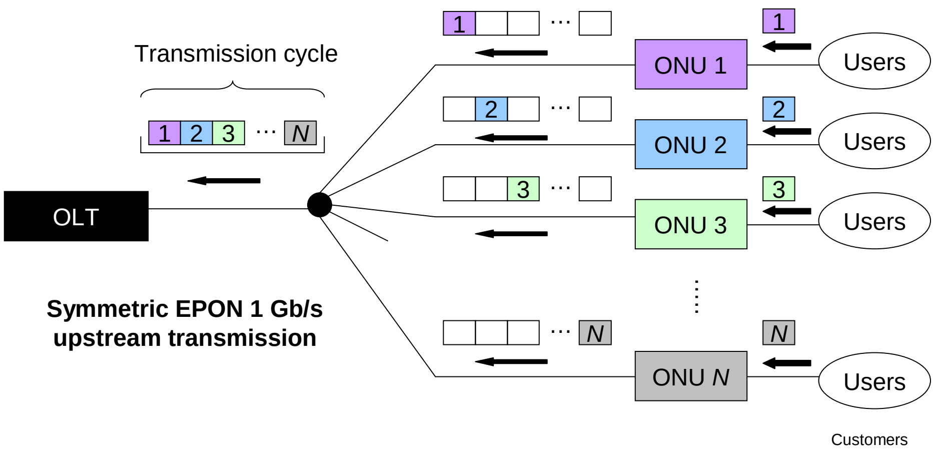

Fig. 1.2: EPON architecture with upstream transmission.

In the upstream direction, each ONU sees the OLT as a point-to-point structure. Therefore, ONUs' traffic must be scheduled so that frames from different ONUs will not overlap after the passive combiner. Due to the Ethernet nature that all Ethernet devices belong to a single collision domain, EPON upstream employs the TDMA technique, which is used to allocate time frame for each ONU to send their frames in order to avoid collision after the passive combiner and effectively share the channel capacity among the ONUs [24]. The upstream TDMA transmission from *N* number of ONUs to the OLT is shown in Fig. 1.2.

Nowadays, most of the local area networks (LANs) and home networks are deployed using Ethernet technology. Therefore, this broad market factor with economies of scale makes EPON technology more cost-effective. Furthermore, EPON's variable length frame format is efficiently used to accommodate IP packets compared to BPON. Despite the advantages of EPON described above, one interesting research problem is related to EPON's efficiency and scalability due to the shared resources in the network. To support a large number of users, and to exploit multiplexing gains from serving bursty Internet traffic, the EPON scheduler should be able to allocate bandwidth dynamically [26]. In response to this challenge, the research community has generated a number of interesting EPON dynamic bandwidth assignment (DBA) proposals [27-30].

In EPON, LAN traffic frames between ONUs are required to travel through the network twice (upstream then downstream after redirection at OLT). Although the 'passive' advantage of PON makes it a cost-effective solution, it also makes EPON an inefficient network in terms of network throughput and LAN traffic delay. Furthermore, this issue will exacerbate as the number of users increase in the network. Therefore, the large scale EPON access networks are in need of an efficient network traffic management scheme to increase data rate availability and reduce packet latency in the presence of higher local traffic.

Another set of research problems is related to the fact that EPON is sought for subscriber access, which is an environment that serves independent and non-cooperative users [26]. Customers pay for service and expect to receive their service regardless of the network state or the activities of the other users. Unlike traditional, enterprise-based Ethernet, the EPON must be able to guarantee service level agreements (SLAs) and enforce traffic shaping and policing for each individual user [26]. Providing DBA, while guaranteeing performance parameters such as packet latency, packet loss, and bandwidth, is yet another challenge. This thesis addresses a number of above research issues and proposes solutions for them. Experimental or simulation demonstrations are presented with theoretical evaluations to identify the performance advantages and practical feasibility of the schemes.

.

1.1.3. WDM-PON

WDM-PON technology has been recognised as one of the most suitable solutions for bandwidth bottleneck in the last mile. Each ONU is serviced by a separate wavelength for upstream and downstream as described in Fig. 1.3. This WDM technique results a formation of virtual point-to-point connection between the CO and ONUs. These virtual point-to-point connections between the SPs and customers enable large bandwidth connections, simple management and enhanced network security [19].

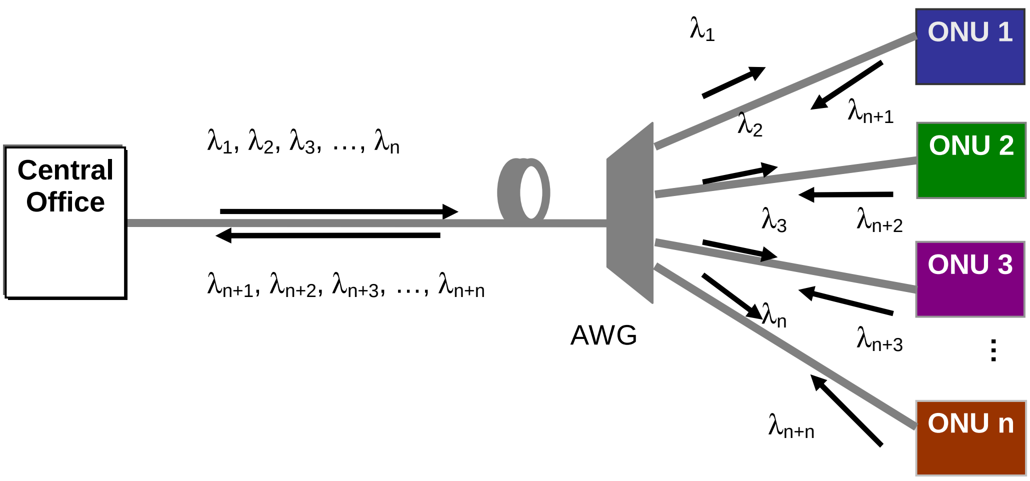

Fig. 1.3: WDM-PON architecture, where λ_1 could be the same as λ_{n+1} and so on depends on architecture design.

Despite the advantages of WDM-PON are clear, the technology is relatively immature. Issues such as location independent low-cost WDM light sources [31-33], delivery of broadcast services, fault monitoring [29] and independent service provisioning are critical for commercial deployment of WDM-PON.

Location independent, low cost WDM light source

WDM-PON uses separate wavelength channels for different ONUs, which results in additional costs with the installation and maintenance of the wavelength selective laser sources. Some of the research solutions have proposed the use of spectrum-sliced incoherent light sources such as light emitting diode (LED) or amplified spontaneous emission (ASE) sources [31-33]. National Information and Communication Technology Australia (NICTA) has also proposed the technique of using subcarrier transmission technique to achieve laser free ONUs [35].

Broadcast services delivery

Virtual point-to-point connection between the CO and the ONUs is the significant advantage of WDM-PON. On the other hand, this advantage turns into inefficiency in WDM-PON's when delivering broadcast services. Researchers have proposed several solutions such as WDM overlay on PON or broadband LED for the broadcast signals [34]. However, WDM overlay on PON requires additional WDM filters and couplers while broadband LED for broadcast signals requires additional pair of fibre and frequency up/down conversion of video signals due to the limitation of LED bandwidth. With these issues in mind, a proposal on using cyclic property of the AWG for delivery broadcast video was demonstrated [34].

Fault monitoring and localisation

Telecommunication SPs will not set up a network if the network can not be managed and monitored for its performance. Therefore, fault monitoring and localisation are vital in successful roll out of WDM-PON. Conventionally, optical time-domain reflectometer (OTDR) is used to localise the fibre failures along the transmission line. However, OTDR operates at single wavelength only and therefore there are limitations in using this technology for WDM-PON. To solve this problem, some of the solutions proposed the use of wavelength tunable OTDR allocated at the remote node [34]. For these solutions, expensive OTDR has to be implemented and consequently increases the network cost and complexity. On the other hand, the technique of detecting fibre failure by monitoring the upstream signals through transmitting OTDR pulses during normal operation eliminates the use of expensive wavelength tunable OTDR and additional light source [36].

Independent services provisioning in WDM-PON

Provisioning of independent services such as video or another such independent service in WDM-PON can be complicated. Several techniques have been proposed to address this issue such as using an additional set of wavelengths separated by the free spectral range of the AWG at the remote node and time multiplexing schemes for both services to share the same wavelength [34]. The second technique requires TDM support components at the CO's OLT and every ONU in order to insert and extract different service traffic streams on the same wavelength. Therefore, these proposed techniques can be complex and costly to implement especially when the independent services are delivered by different SPs. This thesis describes a proposed scheme to address the issue on independent services provisioning in WDM-PON and presents experimental evaluations to identify the performance and feasibility of the scheme.

1.2. Thesis Outline

The objective of this thesis is to investigate and develop architectures and techniques for improving performances in optical access networks incorporating WDM-PON and TDM-PON technologies. The next generation access network should be capable of handling multiple customers' requirements of the network. These requirements should be carried out on the existing access network infrastructure with minimal cost and modification in terms of network protocol. This thesis aims to provide several feasible solutions to a number of customers' requirements such as independent service provisioning in WDM-PON, local traffic quality of service (QoS) in EPON, downstream bandwidth enhancement in large scale optical access network, upstream DBA in EPON and the simplified 10 Gb/s upgrade to current 1 Gb/s TDM-PON system using active forwarding remote repeater node (RN). The novel architectures and technologies for the optical access networks presented in this thesis are categorised into two main groups: the WDM-PON and TDM-PON systems. Chapter 3 investigates the issue of independent services provisioning in WDM-PON. A simple technique of closely separated baseband channels generation and separation is proposed as a solution and demonstrated experimentally to prove the feasibility. In Chapter 4, the issues of inefficient local traffic transmission and bandwidth throughput in current TDM-PON system are discussed. An active RN incorporating layer two forwarding function is proposed for EPON to solve this issue and is discussed in detail. Chapter 5 describes EPON's limitation of delivering high quality broadband services to large scale networks due to the shared downstream bandwidth. With the use of EPON incorporating active RN with layer two forwarding function discussed in Chapter 4, it is shown through simulation and theoretical analysis that the downstream bandwidth can be improved significantly; and alternatively the number of customers can be increased while keeping similar data rates compared to conventional EPON system. Chapter 6 investigates the current important issue of fair and efficient upstream bandwidth allocation in TDM-PON. A simple novel DBA mechanism is proposed to enable upstream data rate enhancement per customer. Chapter 7 discusses the challenges in 10 Gb/s upgrade such as minimising costs and modification of protocol. Here, a solution to minimise deployment cost of 10 Gb/s upgrade for large scale EPON system is proposed without major modification on the existing protocol.

The thesis is organised as follows:

Chapter 2: Literature Review

This thesis begins with a brief introduction to PON systems including WDM-PON and TDM-PON. A brief summary of the WDM-PON is followed by the subcarrier multiplexing techniques, which is widely deployed for optical label switching. A detail description for EPON, an Ethernet technology in TDM-PON is presented followed by essential protocols that support EPON such as multi-point control protocol (MPCP) and DBA. In addition, techniques and optical access architectures that are previously proposed by researchers to improve EPON efficiency such as long reach and high split-ratio optical access systems will be discussed. Finally, the standardisation of the next generation EPON system (IEEE 802.3av 10 Gb/s EPON) will be discussed in brief.

Chapter 3: Independent Services Provisioning in WDM-PON

This chapter discusses the current issue in WDM-PON system for independent services provisioning. It also describes a novel technique that enable simple provisioning of independent services in WDM-PON. The technique uses a single laser and modulator for generation, and a periodic passive filter for separation of two closely separated baseband channels. The experimental and simulation results of the bit error rate performance for two 1.5 Gb/s independent service channels at a frequency separation of only 6 GHz will be presented. Furthermore, the characteristic of subcarrier multiplexing in this scheme will be discussed.

Chapter 4: EPON Incorporating Active Remote Repeater Node with Layer 2 Forwarding

This chapter discusses the limitation of IEEE 802.3ah EPON standard on local traffic emulation. The design and implementation of a simple layer two (or MAC) forwarding scheme for EPON with active remote node (RN) is proposed to increase the network efficiency. A detailed analysis on the technique to improve the latencies on local traffic transmission as well as the external downstream traffic will be carried out in this chapter. A series simulation will be conducted to show a large reduction in traffic delays with the implementation of active RN structure without affecting the EPON protocol. Theoretical analysis of the proposed architecture will be discussed and compared with the simulation results to establish the practicality of the scheme.

Chapter 5: Active RN for Improving Downstream Performance in EPON

This chapter introduces the drivers and the possibilities for high-split PON – the Super-PON and several scalability options. The bandwidth bottleneck issue in optical access system especially for a network that supports a large number of users will be discussed. The chapter then presents the active RN EPON as a viable hybrid alternative for passive networks in reducing this bottleneck and describes the advantages of the active RN in high split-ratio EPON in enhancing the downstream performance not only in terms of delay but also through bandwidth or data rate per user. Both simulation and theoretical analysis will be provided to evaluate the feasibility of this scheme.

Chapter 6: Active RN for Improving Upstream Performance in EPON

In this chapter, a simple DBA method will be used to provide better upstream bandwidth management at low traffic load in active RN augmented EPON. It will show that at high traffic load, DBA scheme will have similar performance compared to static bandwidth allocation (SBA) establishing practicality of the work presented in the previous chapters. By implementing the local traffic prediction-based upstream bandwidth assignment technique (LT-DBA) in the network, both upstream and downstream performance can be improved. Simulation results will be provided to support this proposed technique.

Chapter 7: Evaluation of 10 Gb/s EPON Incorporating Active RN

This chapter discusses a current hot topic of 10 Gb/s upgrade for EPON system. The upgrade is necessary as the bandwidth demand for each user is sky-rocketing due to increased popularity in triple-play services. A simple 10 Gb/s link upgrade between OLT and the active RN with layer two filtering in EPON system can be utilised to achieve the same data rate per user compared to point-to-point upgrade of all ONUs to 10 Gb/s. This scheme will lead to significantly lower initial upgrade costs. Simulation and theoretical analysis on such a proposed architecture will be carried out to explain the feasibility of the scheme.

1.3. Original Contributions

The original contributions to the field of optical access networks contained in this thesis can be summarised as follows. Publications arising from this work are listed in section 1.4.

- **Chapter 3**
  - Proposed a new approach for independent services provisioning in WDM-PON
  - Proposed the use of single laser and modulator for generation of two closely separated baseband channels.
  - Proposed the use of passive periodic filter for separation of two baseband channels at the customer site leading to location independent components at customer units.
  - Evaluated the effect on bit-error-rate (BER) with different amount of radio frequency (RF) power to generate the two baseband channels.
- **Chapter 4**
  - Proposed a layer two forwarding technique incorporated on remote repeater node in EPON named as active RN on EPON.
  - Proposed a frame listening technique in the active RN to enable information gathering of the network connected to it.
  - Proposed shared buffering technique in the active RN to efficiently use the bandwidth for local traffic filtering and redirecting.
  - Proposed a solution to achieve fix delay at the active RN to avoid synchronisation issues due to insertion of RN.

- Proposed a theoretical analysis method on improving local traffic and external downstream delays.

- **Chapter 5**

    - Proposed the use of EPON incorporating active RN with layer two forwarding described in Chapter 4 for long reach and high split-ratio EPON system.

    - Demonstrated the advantage of bandwidth enhancement in high split-ratio EPON system using the proposed architecture.

    - Demonstrate the scalability options of using the active RN in EPON compared to conventional system.

    - Proposed a theoretical analysis method on improving average downstream bandwidth per ONU using active RN in EPON.

- **Chapter 6**

    - Proposed a local-traffic prediction based dynamic bandwidth allocation (LT-DBA) algorithm for excess granting of extra timeslots for EPON upstream transmission.

    - Proposed a subnet-based round robin method for timeslot assignment for distribution link collision avoidance.

    - Proposed a discovery method for ONU physical location for access link collision avoidance.

    - Introduced an upstream scheduler in the active RN to manage upstream transmission for feeder link collision avoidance.

- **Chapter 7**

    - Proposed a simple 10 Gb/s upgrade in EPON incorporating active RN with layer two filtering function.

    - Demonstrated the equal data rates that can be achieved compared to direct conventional point-to-point upgrade using the proposed architecture; while having much lower deployment cost especially in a large scale network.

    - Evaluated on cost analysis of the 10 Gb/s EPON upgrade using active RN with layer two filtering function.

1.4. Publications Arising From The Work Completed In This Thesis

1. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, "Generation and Separation of Closely Separated Dual Baseband Channels for Provisioning of Independent Services in WDM-PON," *IEEE Photonics Tech. Lett.*, vol. 19, no. 16, pp. 1215 – 1217, Aug. 2007

2. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, "Remote Repeater based EPON with MAC Forwarding for Long Reach and High-Split Ratio Passive Optical Networks," *J. Optical Commun. and Networking*, vol. 2, no. 1, pp. 28-37, Jan. 2010.

3. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, "A Local Traffic Prediction-based Dynamic Bandwidth Assignment Scheme for EPON Incorporating Active Filtering Remote Repeater Node," To be submitted.

4. Manik Attygalle, Chien Aun Chan, Thas Nirmalathas, "Closely Separated Dual Baseband Channel Generation and Separation for Provision of Broadcast Traffic in WDM-Passive Optical Networks," in *Proc. Australian Conference on Optical Fibre Technology*, Melbourne, Australia, Dec. 2006.

5. Chien Aun Chan, Manik Attygalle, Thas Nirmalathas, "Provision of Independent Services in WDM-Passive Optical Networks using Closely Separated Dual Baseband Channels," in *Proc. Optical Fibre Communication Conference*, paper JWA48, Anaheim, USA, Mar. 2007.

6. M. Attygalle, C. A, Chan, and A. Nirmalathas, "Optimisation of Drive Amplitude and Stability Analysis for Dual Baseband Channel Generation using a Single Laser and Modulator", in *Proc. International Conference on the Optical Internet/Australian Conference on Optical Fibre Technology*, paper WeA2.3, Melbourne, Australia, Jun. 2007.

7. C. A, Chan, M. Attygalle, T. Nirmalathas, “Improving Network Performance Using Active Remote Node In EPON,” in *Proc. Opto Electronics and Communications Conference/Australian Conference on Optical Fibre Technology*, paper Thp-73, Sydney, Australia, Jul. 2008,.

8. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, “Active Remote node with Layer Two Forwarding For Improving Performance of EPON”, in *Proc. IEEE Global Communication*, New Orleans, USA, Dec. 2008.

9. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, “Local Traffic Prediction-based Bandwidth Allocation Scheme in EPON with Active Forwarding Remote Repeater Node,” in *Proc. 14th Opto Electronics and Communications Conference*, Hong Kong, Jul. 2009.

10. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, “Evaluation on 10/1 Gb/s Asymmetric EPON with Active Filtering Remote Node Design and Modelling,” in *Proc. Optical Network Design and Modelling Conference*, Japan, Feb. 2010.

1.5. References

[1] Kramer, G, Tanaka, K, "Advances in optical access networks," in Proc. Optical Fibre Communication Conf. (OFC '05), vol. 4, pp. 6-11, Mar. 2005.

[2] H. Frazier, G. Pesavento, "Ethernet takes on the first mile," *IT Professional*, vol. 3, no. 4, pp 17-22, July-Aug. 2001.

[3] G. Kramer and G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," *IEEE J. Commun. Mag.*, vol. 40, no. 2. pp. 66-73, 2002.

[4] G. T. Hawley, "Historical perspectives on the US telephone loop," *IEEE Commun. Mag.*, vol. 29, no. 3. pp. 24-28, Mar. 1991.

[5] V. K. Bhagavath, "Emerging high-speed xDSL access services: architectures, issues, insights, and implications," *IEEE J. Commun. Mag.*, vol. 37, no. 11. pp. 106-114, Nov. 1999.

[6] D. Cuffie, K. Biesecker, C. Kain, G. Charleston, and J. Ma, "Emerging high-speed access technologies," *IT Professional*, vol. 1, no. 2. pp. 20-28, Mar. 1999.

[7] C. Lin, K.-L. Deng, and C.-K. Chan, "Broadband optical access networks," in Proc. *4th Conference of Lasers and Electro-Optics*, vol. 2, pp. 576-577, Jul. 2001.

[8] D. W. Faulkner, D. B. Payne, J. R. Stern, J. W. Balance, "Optical networks for local loop applications," *IEEE J. Lightwave Technol.*, vol. 7, pp. 1741-1751, Nov. 1989.

[9] D. Kettler, H. Kafka, D. Spears, "Driving fibre to the home," *IEEE Commun. Mag.*, vol. 38, pp. 106-110, Nov. 1994.

[10] M. Shibutani, H. Ishikawa, H. Tezuka, W. Domon, M. Soda, K. Emura, "A gigabit-to-the-home (GTTH) system for future broadband access infrastructure," *IEEE International Conference on Communications*, vol. 2, pp. 1004-1008, 1997.

[11] N. J. Frigo, "Optical networking for local access," in *Proc. IEEE/LEOS Summer Topical Meetings in Advanced Applications of Lasers in Materials Processing, Broadband Optical Networks – Enabling Technologies and Applications, Smart pixels: Optical MEMS and their Applications*, pp. 39-40, Aug. 1996.

[12] N. J. Frigo, "Recent progress in optical access network," in *Proc. Optical Fibre Communication Conference*, pp. 142-143, Feb. 1996.

[13] Y. Maeda, "ATM-PON FTTH access networks and services," in *Proc. Optical Fibre Communication Conference*, vol. 3, pp. 21-26, Feb. 1999.

[14] F. J. Effenberger, H. Ichibangase, H. Yamashita, "Advances in broadband passive optical networking technologies," *IEEE J. Commun. Mag.*, vol. 39, no. 12, pp. 118-124, Dec. 2001.

[15] I. Cale, A. Salihovic, M. Ivekovic, "Gigabit Passive Optical Network – GPON," in *Proc. 29th International Conference on Information Technology Interfaces*, pp. 679-684, Jun. 2007.

[16] ITU-T recommendation G.894.1, "Gigabit-capable passive optical networks (GPON): General characteristics," Mar. 2008, available at: http://www.itu.int/rec/T-REC-G.984.1-200803-I/en.

[17] IEEE 802.3 ah EFM standard, (part of IEEE std 802.3), available online at http://standards.ieee.org/getieee802.

[18] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, B. Mukherjee, "Wavelength-Division Multiplexed Passive Optical Network (WDM-PON) Technologies for Broadband Access: A Review," *OSA J. Optical Networking*, vol. 4, no. 11, pp. 737-758, Nov. 2005.

[19] Novera Optics, "WDM-PON for the Access Network," Novera Optics Inc. white paper, available online at http://www.noveraoptics.com.

[20] B. Hukherjee, "Optical WDM networks," Springer, 2006, ISBN: 978-0-387-29055-3.

[21] G. Kramer, "What is next for Ethernet PON?" in *Proc. of the 5th International Conference on Optical Internet*, July 2006.

[22] G. Kramer, "Ethernet Passive Optical Networks," McGraw-Hill Professional, ISBN: 0071445625, Chapter 3, pp 25-32.

[23] G. Kramer, "Ethernet Passive Optical Networks," McGraw-Hill Professional, ISBN: 0071445625, Chapter 5, pp 45-64.

[24] G. Kramer, "Ethernet Passive Optical Networks," McGraw-Hill Professional, ISBN: 0071445625, Chapter 8, pp 85-138.

[25] S. Clavenna, "Metro optical Ethernet," Lightreading Telecom Report, Nov. 2000 available at http://www.lightreading.com/document.asp?doc_id=2472.

[26] G. Kramer, "Ethernet Passive Optical Networks," McGraw-Hill Professional, ISBN: 0071445625, Chapter 4, pp 33-42.

[27] C. M. Assi, Y. Yinghua, D. Sudhir, M. A. Ali, "Dynamic bandwidth allocation for quality-of-service over Ethernet PONs, " *IEEE J. Sel. Areas Commun.*, vol. 21, no. 9, pp. 1467-1477, Nov. 2003.

[28] H.-J. Byun, J.-M. Nho, J.-T. Lim, "Dynamic bandwidth allocation algorithm in Ethernet passive optical networks," *IEE Electron. Lett.*, vol. 39, no. 13, pp. 1001-1002, Jun. 2003.

[29] G. Kramer, B. Mukherjee, G. Pesavento, "IPACT a dynamic protocol for an Ethernet PON (EPON)," *IEEE J. Commun. Mag.*, vol. 40, no. 2, pp. 74-80, Feb. 2002.

[30] I. S. Hwang, Z. D. Shyu, L. Y. Ke, C. C. Chang, "A novel early DBA mechanism with prediction-based fair excessive bandwidth allocation scheme in EPON," *Comp. Commun.*, vol. 31, no. 9, pp. 1814-1823, Jun 2008.

[31] M. H. Reeve, A. R. Hunwicks, W. Zhao, S. G. Methley, L. Bickers, S. Hornung, "LED spectral slicing for single-mode local loop applications," *IEE Electron. Lett.*, vol. 24, no. 7, pp. 389-390, Mar. 1988.

[32] D. K. Jung, S. K. Shin, C. –H. Lee, Y. C. Chung, "Wavelength-division-multiplexed passive optical network based on spectrum-slicing techniques," *IEEE Photon. Tech. Lett.*, vol. 10, no. 9, pp. 1334-1336, Sep. 1998.

[33] K. H. Han, E. S. Son, K. W. Lim, H. Y. Choi, S. P. Jung, Y. C. Chung, "Bi-directional WDM passive optical network using spectrum-sliced light-emitting diodes," in *Proc. Optical Fibre Communication Conference*, vol. 1, pp. 23-27, Feb. 2004.

[34] Y. C. Chung, "Challenges Toward Practical WDM PON," in *Proc. Optoelectronics and Commununication Conference*, paper 6C4-1, 2006.

[35] M. Attygalle, T. Anderson, D. Hewitt, A. Nirmalathas, "WDM passive optical network with subcarrier transmission and baseband detection scheme for laser-free optical network units," *IEEE Photon. Tech. Lett.*, vol. 18, no. 11, pp. 1279-1281, Jun. 2006.

[36] K. W. Lim, E. S. Son, K. H. Han, Y. C. Chung, "Fault localization in WDM passive optical network by reusing downstream light sources," *IEEE Photon*. *Tech*. *Lett*., vol. 17, no. 12, pp. 2691-2693, Dec. 2005.

2 Literature Review

2.1. Introduction

In the early stage of the development of the access network, the motivation was to deploy a higher quality and more responsive 'first mile' network for the delivery of conventional telephony and data services [1]. However, the traffic patterns in the access networks have evolved from voice and text oriented services to video and image-based services driven by the exploding growth of Internet and its applications [2, 3]. This dramatic change in the dominant composition of the network traffic in access networks urges the service providers to deploy a new access network architecture that can offer high speed, symmetric and guaranteed bandwidths to converge voice, data and video traffic (triple-play services) with a focus for future high bandwidth demand services [4, 5]. As a consequence, the introduction of optical transmission systems into access networks appears to be the most promising technique to provide huge bandwidth for both downstream transmission link from the central office (CO) to the customer premises and the upstream transmission link from the customer premises to the CO [6-9]. Among a number of proposed architectures to provide optical connectivity between the CO and customer premises such as point-to-point links, active optical networks (AONs) and passive optical networks (PONs); PONs have been regarded as the most suitable next generation optical access network architecture due to their simplicity and low cost [10-14].

Chapter 1 briefly discussed the categories, basic functions and benefits of PON systems. The point-to-multipoint PON system that connects the optical line terminal (OLT) at service provider's CO to optical network units (ONUs) at multiple customer premises requires multiplexing techniques to enable sharing of bandwidth among customers. The time division multiplexing (TDM) PON system uses power splitter (downstream)/combiner (upstream) to enable customers sharing on single wavelength in directions by using allocated time-slots [15-19]. In contrast, wavelength division multiplexing (WDM) PON system uses arrayed waveguide grating (AWG) for multiplexing and de-multiplexing of dedicated wavelengths pairs [20-24] allocated for each customer for upstream and downstream directions. As the traffic demand by customers in the access network increase, bandwidth efficiency in the TDM-PON system becomes a critical issue. The natural limitation of using passive components in TDM-PON causes local inter-ONU communications to be redirected at the OLT and travel through the feeder fibre link twice (upstream then downstream) before reaching the destination ONU. This issue becomes serious when the number of supporting ONUs in the network is increased to cover a larger customer base. Furthermore, dynamic bandwidth assignment (DBA) mechanism that is opened for the vendors to customisation as a way of differentiating their products in the market, has been a hot research topic among researchers to better utilise the shared upstream bandwidth in TDM-PON.

Since the deployment of PON system, the end users are able to enjoy large bandwidth and high-quality services. Killer applications such as Internet protocol television (IPTV), video-on-demand (VoD), video conferencing and interactive gaming, which are enabled by gigabit-capable optical access networks, have been accepted by the subscribers with great enthusiasm and driven the demand for more bandwidth-intensive applications and services such as high-definition television (HDTV) that will consume 8-10 Mb/s per channel [25]. Therefore, the conventional 1 Gb/s TDM-PON becomes insufficient to provide quality of service (QoS) to support such high bandwidth demand applications. This resulted in the commencement of standardisation of next generation TDM-PON system [26]. On the other hand, WDM-PON system that has many advantages over TDM-PON such as higher bandwidth, protocol transparency and more security; is only widely demonstrated within research projects and currently immature for commercial consideration. [27-30].

In this chapter, some of the previously demonstrated advanced functionalities of WDM-PON in provisioning independent services (such as video, etc.) and subcarrier multiplexing (SCM) will be discussed. Furthermore, the detailed functions of Ethernet PON (EPON) and several open research issues such as long reach and high split-ratio PON as well as various DBA mechanisms and the upgrade of 10 Gb/s EPON will be presented. Section 2.2 discusses a number of previously proposed SCM schemes in WDM-PON technology. Section 2.3 presents the detailed functions of the IEEE 802.3ah standard of 1G-EPON system. Section 2.4 will carry out discussions on various projects to enable long reach and high split-ratio PON system in order to increase the number of customers and improve the network coverage. Section 2.5 describes a number of previously proposed DBA mechanisms on improving the upstream transmission efficiency for a TDM-PON. In section 2.6, the current standardisation of 10 Gb/s EPON and various upgrade options will be discussed. Finally, section 2.7 will summarise the overall chapter.

2.2. Independent Services Provisioning in WDM-PON

As the next generation optical access technology, WDM-PON has obvious advantages over TDM-PON especially in the bandwidth per user since a dedicated wavelength is assigned to each ONU. However, the immature technology of WDM-PON system has raised several research issues for researchers to address. If independent services such as video services provided by either the same vendor or a different service provider have to be overlaid onto the WDM-PON system, the basic solution would be using an additional set of wavelengths separated by the free-spectral-range (FSR) of the AWG [31].

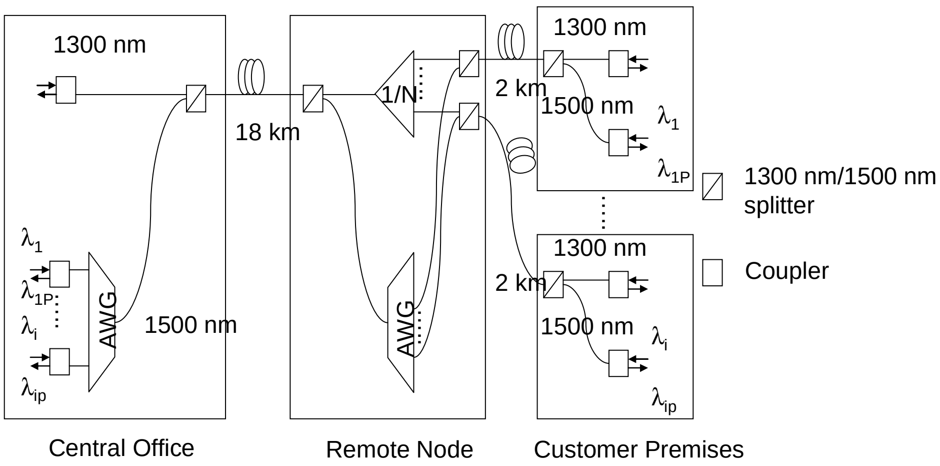

Fig. 2.1: WDM upgrade for PON [31].

The Institute for Communication Technology from Braunschweig Technical University has proposed a technique for delivery of broadcast video service on different wavelength channel [31]. As shown in Fig. 2.1, the 1300 nm window is used to cover all basic services while the power splitter of 1:*N* (where *N* represents the number of ONUs) is upgraded for the use of 1500 nm window without interfering the existing 1300 nm window. A 1:*N* AWG is installed in the CO to multiplex *i* wavelength channels in 1500 nm window separated by 100 GHz (AWG's FSR) and combined with basic services on 1300 nm channels at the power splitter/combiner. A second AWG, which has identical FSR as the first AWG is used at the remote node (RN) routes the wavelengths to corresponding individual ONUs. In the upstream direction, the upstream wavelength λ_{iP} has to be selected to use the same path through the AWGs as the downstream signals. However, the downside of this proposed scheme appears to be the requirement of a large number of WDM filters and couplers [31].

Besides the solution of using an additional set of wavelengths separated by the FSR of the AWG to provision independent services, other techniques have also been proposed by using the broadband light emitting diodes (LEDs) for the delivery of broadcast channels [32]. The American Telephone & Telegraph (AT&T) research laboratory has proposed that multiple independent broadcast services can be delivered efficiently over a common WDM-PON system such as 1) delivery of two independent video services using uncooled LEDs, each modulated with independent sets of 80 digital video channels on 16 quadrature phase-shift keying (QPSK) subcarriers in 50 to 550 MHz radio frequency (RF) band and optical filtering with multilayer dielectric optical bandpass filters (OBPF) centred at 1545 nm and 1556 nm (for two video channels), 2) a bidirectional 50 Mb/s baseband conventional TDM-PON service, 3) a limited (50 channels) digital broadbast video service and 4) an individual 2.5 Gb/s bidirectional link to a “business’ subscriber [32]. The ONU at the customer premise can be customised to filter unwanted service. However, frequency up/down conversion of video signals due to the limited modulation bandwidth of LED becomes the limitation to this proposed scheme [33]. As a result, the Korea Advanced Institute of Science and Technology (KAIST) has demonstrated the implementation of a bidirectional WDM-PON capable of transmitting both digital broadcast video signals at 1550 nm wavelength region (at 2.5 Gb/s) and WDM data channels at 1530 nm wavelength region with more than 70 digital channels; while the upstream data channels are operating at 1300 nm at data rate of 155 Mb/s using LEDs [33]. However, a large number of couplers are required to separate the three wavelength channels at the RN (where the AWG is located) and at every ONU [33].

2.2.1. Subcarrier multiplexing technique in WDM-PON

Originally, SCM technique in optical domain has been studied in [34] and [35] for crosstalk analysis. Although SCM technique is also widely used for Hybrid Fibre/Coaxial systems (HFC) [36], several recent proposals involve the use of subcarrier signals to generate relatively low speed additional data channels such as control signals or labels in label switching networks. Optical label switching is a promising approach to switch and route packets at ultrahigh bit rates in the optical layer [37-40]. In [37], RF photonics signal processing to carry label signal applied to single sideband and double sideband subcarrier signals have been demonstrated as shown in Fig. 2.2 (a) and (b) respectively.

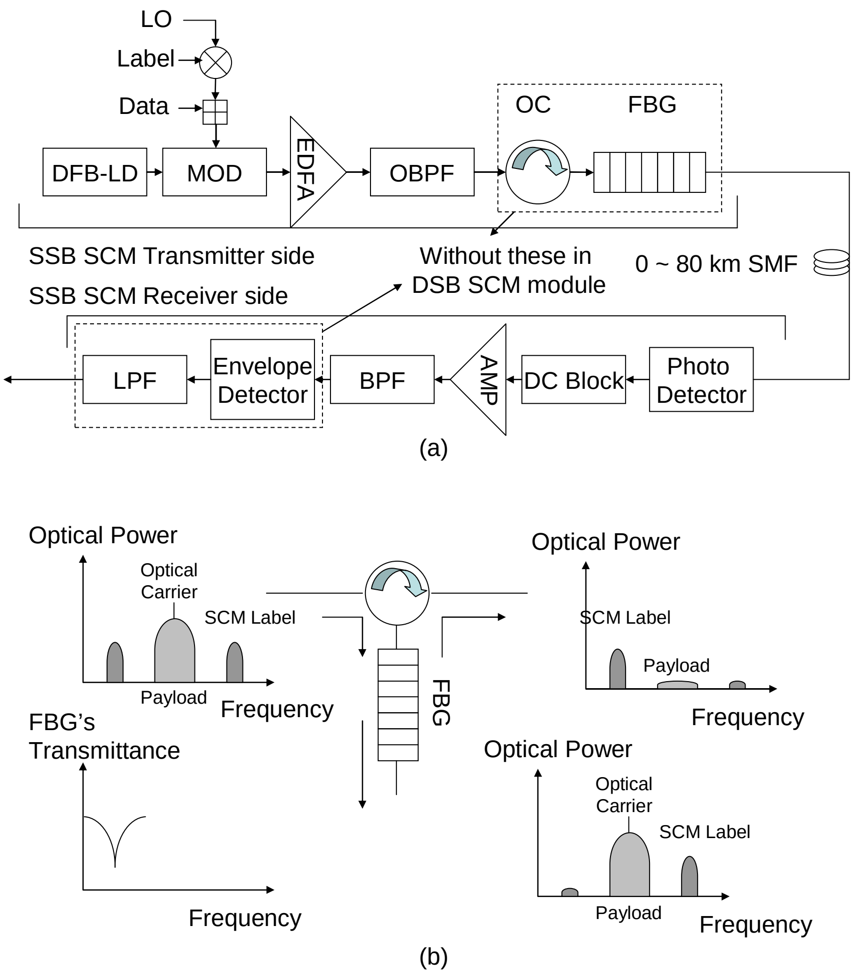

Fig. 2.2: (a) shows the SSB and DSB SCM generation. DFB-LD: DFB laser diode; LO: electrical local oscillator; MOD: optical modulator; OBPF: optical bandpass filter; SMF: single mode fibre; LPF: electrical low pass filter; AMP: RF amplifier; BPF: electrical bandpass filter. (b) shows the generation of SSB SCM signal using OC and FBG [37].

Refer to Fig. 2.2 (a), the SCM label signal is a 155 Mb/s non-return zero (NRZ) amplitude shift keying (ASK) modulated signal on a 14 GHz RF carrier. The centre wavelength generated by the distributed feedback laser diode (DFB LD) is 1557.36 nm with a payload of 2.5 Gb/s in NRZ format. The combined payload and RF label optical signal is then being filtered by the fibre brag gating (FBG) to reject one SCM sideband to produce the single sideband SCM with data payload signal. This optical signal will then be sent to the ONU for label detection as shown in Fig. 2.2 (a). The generation of SSB SCM signal using optical circulator (OC) and FBG is shown in Fig. 2.2 (b). In order hand, double sideband SCM optical signal does not require the OC and FBG. However, a RF spectrum analyser is needed at the receiver side to measure the subcarrier power and a RF circuit is used to filter out the baseband payload signal and hence downshift the subcarrier component to obtain the label information [37].

On the other hand, [38] has demonstrated the subcarrier label swapping subsystem with 2R (re-amplification, reshaping) optical regeneration and wavelength conversion techniques. A label signal with a data rate of 155 Mb/s is subcarrier multiplexed with a 2.488 Gb/s data carrier signal. After receiving the combined signal, the data payload signal will be sent to the label-rewriting module. The label-rewriting module as shown in Fig. 2.3 contains a DFB LD, a modulator, a semiconductor optical amplifier (SOA) based Mach-Zehnder interferometer wavelength converter (MZI WC), a FBG and an Erbium doped fibre amplifier (EDFA). The DFB LD provides continuous wave light to both arms through a 1 × 2 fibre coupler where one arm will undergo the cross-phase modulation wavelength conversion with 2R regeneration through the MZI WC [38, 40, 41] while the other arm will generate new label content through modulating the SCM signal [38]. Compared to above proposed scheme, [39] uses similar technique to generate SCM label signal (RF carrier at 14 GHz with 622 Mb/s label signal rate) for performance monitoring.

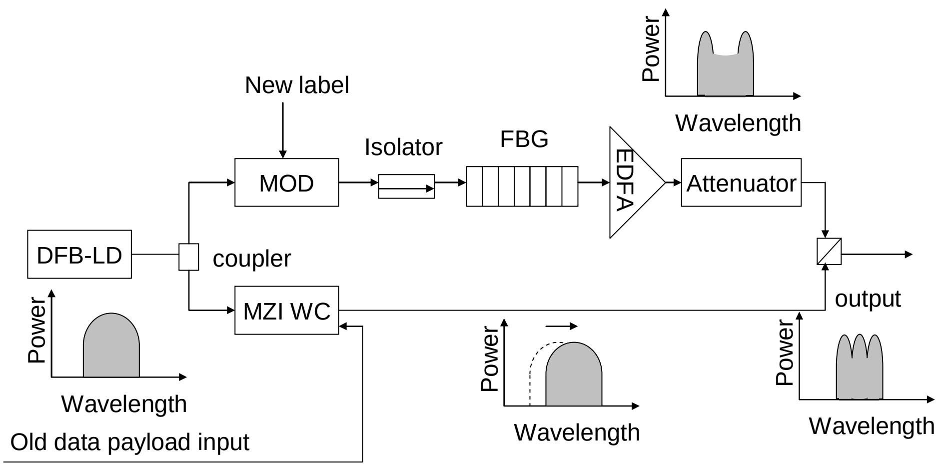

Fig. 2.3: Label rewriting module for SCM signal generation [38].

Compared to the SCM techniques in [37-40] (14 GHz RF carrier), [42] and [43] use lower frequency for subcarrier signals. As shown in Fig. 2.4, two independent 2.5 Gb/s data streams are upconverted to 6 GHz and 15.5 GHz. A 1550 nm carrier signal is externally modulated with the two subcarrier multiplexed signals using a MZI modulator. At the receiver side, fibre Fabry Perot (FFP) filter is used to optically filter unwanted subcarrier signal. Similar to [42], instead of two independent data channels, [43] uses four independent data streams (2.5 Gb/s) at RF carrier frequencies of 3.9 GHz, 9.3 GHz, 14.3 GHz and 19.2 GHz respectively; while corresponding FFP filter will be used at the receiving side to preselect desired subcarrier sidebands. Most of these demonstrations have utilised high speed receivers and phase locked loops to detect the subcarrier signals [42, 43].

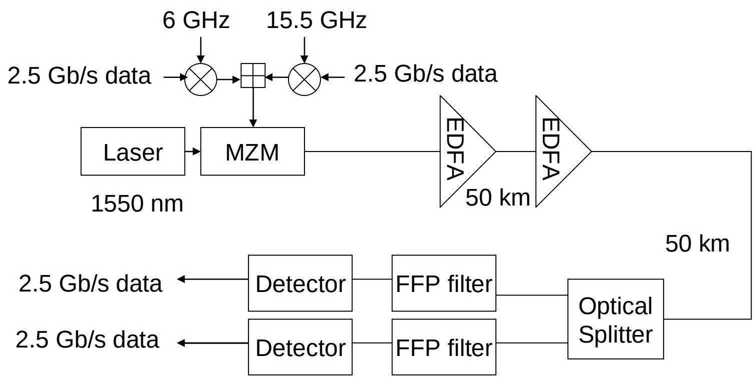

Fig. 2.4: Block diagram for SCM system in [42].

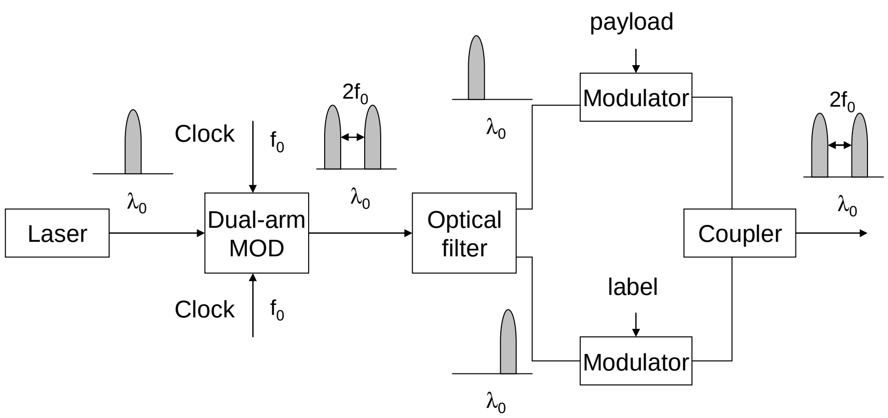

Fig. 2.5: Generation of optical label and payload using OCSS technique in [46].

Besides subcarrier techniques that utilise RF local oscillator to mix data stream or label signal into the RF carrier, [44-46] proposed the optical carrier suppression and separation (OCSS) to carry payload and label information on an optical carrier. The OCSS technique uses a dual arm Lithium Niobate ($LiNbO_3$) modulator (LN-MOD) with RF of f_0 to generate a two longitudinal optical modes as shown in Fig. 2.5 [46]. The two longitudinal modes are separated by optical filtering, and then modulated by two individual intensity modulators to generate two individual optical payload and label subcarrier channels [46]. These two signals are then combined at the coupler and transmitted downstream to the receiver sides.

Drawbacks of SCM include the reduced extinction ratio of the constituent data streams and the requirement for additional RF photonic components at the transceivers. However, SCM technique can be effectively utilised for optical domain independent services provisioning in WDM-PON as demonstrated in Chapter 3. The next section focuses on the current TDM-PON standard, and the EPON system will be discussed in detail.

2.3. Ethernet Passive Optical Network (EPON)

As discussed in Chapter 1, EPON and Gigabit PON (GPON) have been widely deployed around the world. GPON is defined by ITU-T recommendation G.984 as an enhancement to asynchronous transfer mode PON (A-PON) and broadband PON (BPON) [47]. It is designed to transport Ethernet, ATM and TDM traffic using GPON encapsulating method (GEM) [48]. In contrast, EPON was studied by the Ethernet in the first mile (EFM) group in year 2001 and standardised in year 2004 [49]. The IEEE 802.3ah EFM group provides the standard for a point-to-multipoint, fibre to the premises (FTTP) network architecture using the existing IEEE 802.3 Ethernet technology for packet data transmission in access network through optical fibre medium [50]. The EFM study group has demonstrated the attributes of EPON architecture in terms of broad market potential, technical and economic feasibilities as well as compatibility with IEEE 802 architecture [50]. Since the deployment of PON system, the end users are able to enjoy large bandwidth with high quality of service (QoS). Thirty million lines have been deployed worldwide and the rate of EPON deployments is accelerating since the standardisation of 1 Gb/s EPON in year 2004 [51].

2.3.1. EPON with the Open Systems Interconnection (OSI) reference model

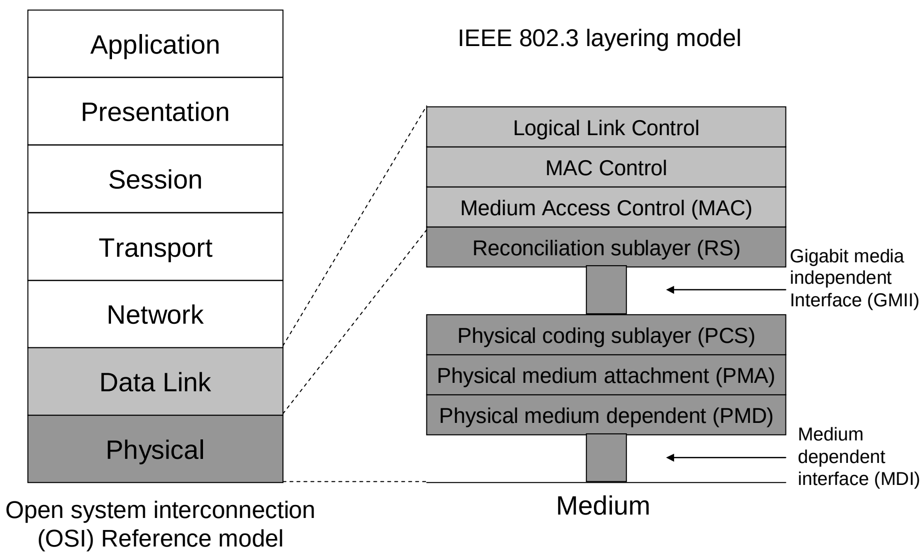

Fig. 2.6: IEEE 802.3 Ethernet layering model in OSI reference model.

The IEEE 802.3 Ethernet standard define the details of the technology in the two lower layers of the Open Systems Interconnection (OSI) reference model, which are the physical and data link layer as shown in Fig. 2.6. Each of the two layers is further divided into sub-layers and interfaces that connect between layers. Therefore, the IEEE 802.3ah EPON system that is built on top of the IEEE 802.3 Ethernet technology will include components on extending the physical medium dependent, reconciliation, physical coding and physical medium attachment sub-layers specifications as well as the point-to-multipoint protocol specification (refer to Fig. 2.6) [49-50, 52-53].

a) Physical medium dependent sub-layer (PMD)

   The PMD sub-layer acts as an interface of the transmission medium and the objectives are to support a point-to-multipoint media using optical fibre at the data rate of 1000 Mb/s for 1:16 splits of up to 10 km and 20 km range operation (from OLT to ONU) [49]. As a result, the PMD timing parameters have been standardised to 512 ns for laser-on and off time and the gain adjustment time is negotiable between OLT and ONUs to be ≤ 400 ns [49-50, 52-53].

b) Reconciliation sub-layer (RS)

   In this sub-layer, gigabit media independent interface (GMII) that specifies an interface between a gigabit-capable MAC and a gigabit physical layer (PHY) is mapped to the media access control service definitions. According to IEEE 802 architecture standard, the connecting devices can communicate with each other directly, therefore the bridge will not forward a frame back to its incoming port [50]. However, the passive splitter in the network only allows optical signal to travel in a single direction and inter-ONU communications are required to go through OLT. This raises an issue in EPON that needs to be compliant with IEEE P802.1D bridging standard [54]. As a consequence, an extension on the reconciliation sub-layer is formed for logical topology emulation, which relies on tagging the Ethernet frames with logical link IDs in the preamble of each frame. The next section will give a detailed discussion on this extension [49-50, 52-53].

c) Physical coding sub-layer (PCS)

   As discussed in Chapter 1, the upstream transmission of an EPON system uses time division multiple access (TDMA) technology as only one ONU is allowed to transmit traffic upstream at any time. Therefore, the ONUs' lasers should be turned off between their transmissions to avoid spontaneous emission noise from short distance ONUs obscuring the signal from long distance ONUs [50]. Part (a) described the laser turn-on and off times in the standard. However, to control the laser to be switched on and off precisely, the PCS is extended to detect data being transmitted by higher layers. Furthermore, the PCS has also been extended to cover an optional forward error correction (FEC) mechanism using Reed-Solomon (RS) code (255, 239) that can increase the optical link budget or transmission distance [49-50, 52-53].

d) Physical medium attachment (PMA) sub-layer

In this sub-layer, an extension to identify a time interval that is required by the receiver to acquire phase and frequency lock on the incoming data stream is specified. This time interval is known as the clock and data recovery (CDR) [50]. This specification requires the OLT to become synchronised at the bit level within 400 ns and at the code-group level within an additional 32 ns [49-50, 52-53].

e) Point-to-multipoint protocol

The point-to-multipoint protocol in EPON represents an important element in order to make EPON an efficient shared access network system. A MAC control-based protocol named the multipoint control protocol (MPCP) is defined in the EPON standard to allow the OLT to assign specific transmission timeslot to each ONU. The MPCP operations are categorised into auto-discovery (used to detect newly joined ONUs in the network and learn their information) and normal modes (used to assign transmission timeslot to the ONUs), which will be discussed in detail in the following section [49-50, 52-53].

2.3.2. Multipoint Control Protocol (MPCP)

As discussed in the previous section, MPCP is a unique protocol in EPON that is responsible in controlling the ONUs' upstream transmissions. In the bandwidth assignment mode (normal mode), a GATE message is sent from the OLT to a particular ONU to notify its time interval to begin transmission and the length of the transmission. These two time intervals are determined by the DBA agent and scheduler at the OLT after receiving the REPORT message from the ONU from the previous transmission cycle [50]. A REPORT message is a feedback mechanism used by the ONU to communicate with the OLT regarding its local conditions such as the buffers' size in order to assist the DBA agent in the OLT to fairly allocate transmission timeslots [49-50, 52-53]. However, the DBA algorithm is out of the IEEE

802.3ah scope and is opened to the equipment vendor to customise as a way of differentiating their products in the market.

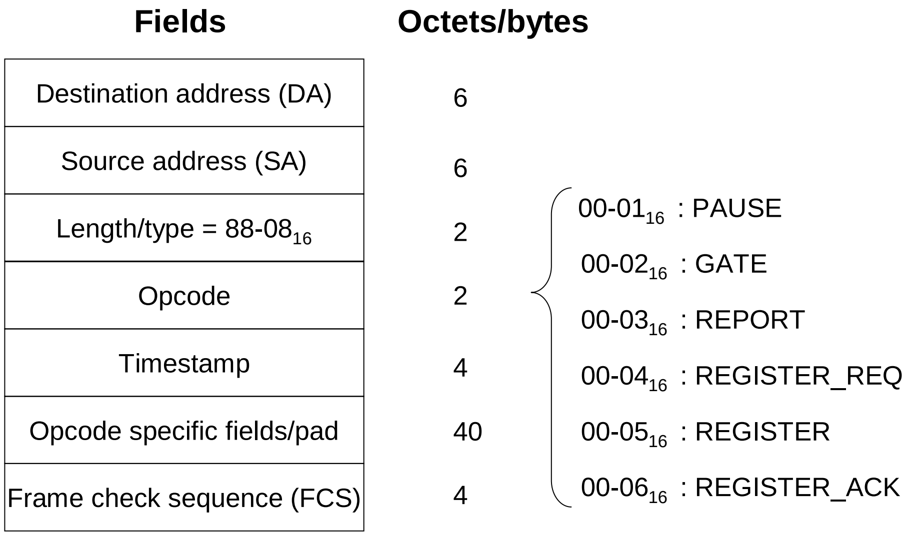

Fig. 2.7: MPCP frame format with six opcode values [50].

As presented in Fig. 2.7, the format of the MPCP frame includes a six-byte destination address (DA), which represents the MAC address of the intended station (OLT or ONU) that it is intended to. The six bytes source address (SA) represents the MAC address of the station that sends the frame while the length/type states the length or type of the MPCP frame. The Opcode field identifies the MPCP frame to be one of the six types – PAUSE, GATE, REPORT, REGISTER_REQ, REGISTER and REGISTER_ACK as shown in Fig. 2.7 [50]. The timestamp field are used to synchronise the MPCP clocks in the OLT and ONUs and the opcode-specific fields are used to carry the information pertinent to specific MPCP functions [50]. The final segment of FCS carries a cyclic redundancy check (CRC) value used by the MAC to verify a proper received frame without errors [49, 50].

At the initial state when a newly powered up ONU intends to join the EPON, it will respond to the periodically sent discovery GATE message from the OLT by sending the REGISTER_REQ message [49]. To register the un-initialised ONU, the OLT will reply the register request by sending the ONU the REGISTER and normal GATE messages for the ONU to reply [49]. Finally, the ONU will acknowledge the register process by sending the OLT a REGISTER_ACK message to complete the discovery handshake process [49]. Please note that the MPCP auto-discovery process will be discussed in depth in Chapter 4 where in depth understanding of the process is important for that chapter.

2.3.3. Round trip time (RTT) measurement

As discussed in the previous section, the timestamp field in all MPCP frames are used to assist in synchronising the MPCP clocks in the OLT and each ONU. Synchronisation between the ONUs and the OLT is important in EPON in order to perform precise upstream timeslot allocation for each ONU to avoid collision at the power splitter/combiner. This synchronisation is done by measuring the round trip time (RTT) from a particular ONU [50]. The initial RTT information regarding an ONU is done in auto-discovery mode [50]. The OLT will set its local MPCP clock time in the timestamp field in the discovery GATE message frame. After receiving the frame by the un-initialised ONU, the ONU will set its local time based on the value in the timestamp field of the discovery GATE message or t_0 as shown in Fig. 2.8 [50]. To register into the network, the ONU will send the REGISTER_REQ message including its local time, t_1 in timestamp field. After receiving the message at the OLT at time t_2, OLT can calculate the distance or RTT of the ONU as follow [50]:

$$RTT_{ONU\_x} = T_{downstream} + T_{upstream} = T_{response} - T_{wait} = (t_2 - t_0) - (t_1 - t_0) = \mathbf{t_2 - t_1}$$

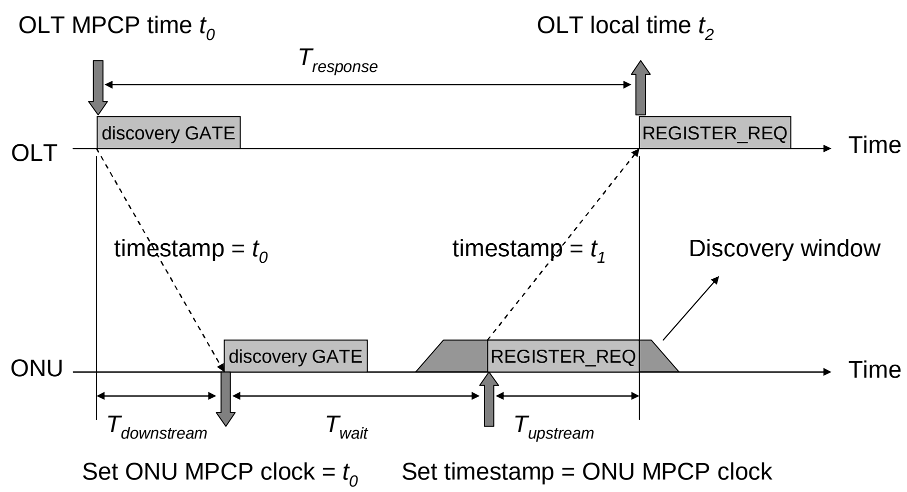

Fig. 2.8: Round trip delay measurement [50].

2.3.4. Logical Topology Emulation (LTE)

The IEEE 802.3 Ethernet standard assumes that all communicating stations in a LAN segment to be connected to a shared medium or single domain [49]. It assumes that all stations in the shared medium that connect to a bridge port will have the capability to communicate with each other through carrier-sense multiple access with collision avoidance (CSMA/CD) [54]. Therefore, the bridge that connects the stations in the LAN segment will never forward a frame back to its incoming port. However, due the directivity of the passive splitter/combiner, users connecting to different ONUs, which require the OLT bridge/switch to redirect the inter-ONU frames will be forbidden based on the earlier statement. As a result, this issue raised a question on EPON compliance with IEEE 802 architecture, particularly with P802.1D bridging standard [49, 50]. To address this issue, devices attached to the PON medium will implement a logical topology emulation (LTE) function, which requires tagging of Ethernet frames with unique logical link identity (LLID) address that are placed in the preamble at the beginning of each frame [49, 50]. The LTE function configuration is based on either a shared medium or a point-to-point medium [56-60].

a) Point-to-point Emulation (P2PE) [56-60]

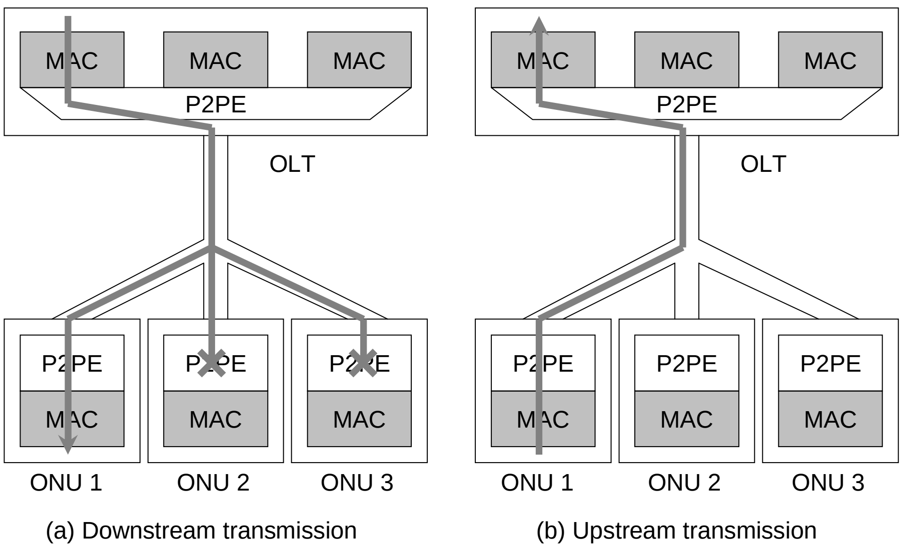

Fig. 2.9: P2PE mode for (a) downstream and (b) upstream transmissions.

The objective of the P2PE mode is to achieve the same physical connectivity as in basic LAN switching standard, where all ONUs are connected to the OLT switch using emulated point-to-point links as shown in Fig. 2.9 [50]. In the OLT, *N* MAC ports that are associated to *N* ONUs are needed and each MAC port at the OLT will be assigned the same LLID as its corresponding ONU [56-60]. When the OLT sends a frame to an ONU with the associated LLID, the frame will pass through the passive splitter/combiner and arrive at each ONU. However, only one ONU will have the P2PE function to match the arriving frame's LLID and accept the frame while other ONUs will discard the frame and the MAC sub-layers will never see the frame to be compliant with IEEE 802 standard [56-60]. In the other hand, the ONU will insert its assigned LLID in each transmitted frame and the P2PE function in the OLT will forward the frame to the proper MAC port based on the unique LLID as shown in Fig. 2.9. For inter-ONU communications, the frames will be de-multiplexed and sent to the OLT switch and then forwarded to the MAC port, which is associated to the destination ONU.

b) Shared-Medium Emulation (SME) [56]

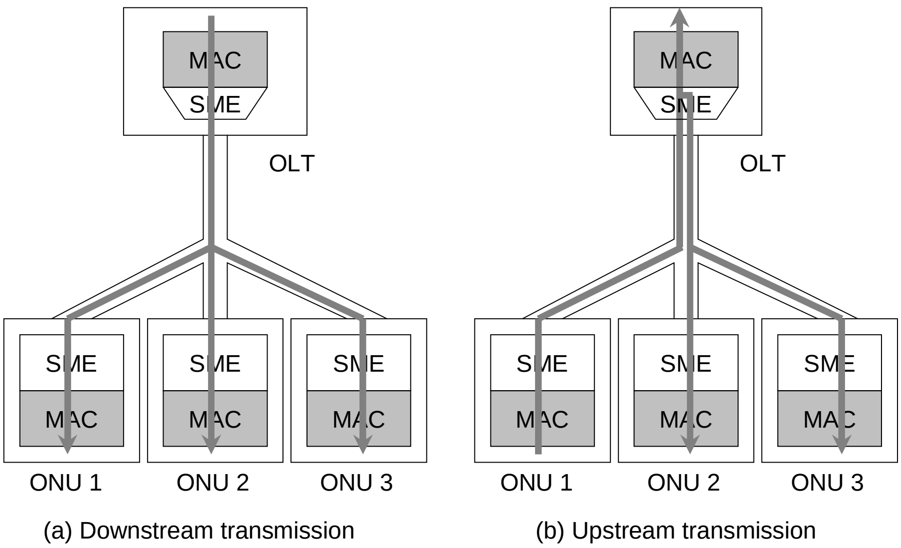

Fig. 2.10: SME mode for (a) downstream and (b) upstream transmissions.

In the SME environment, frames transmitted by any ONU should be received by every ONU except the sender ONU. Therefore, only a single MAC port is used in the OLT regardless of the number of ONUs [56]. In the downstream direction, the OLT inserts a broadcast LLID that will be accepted by every ONU [56]. In the upstream direction, the

OLT will reflect every arriving frame downstream at the LTE function sub-layer to ensure shared-medium operation. Thus, the ONU's LLID filtering rules are opposite to those in P2PE mode (accepts all frames which the LLIDs match its own LLID) [56].

c) Final solution [50, 60]

Although both P2PE and SME functions provide the solution for P802.1D standard compliance issue, the P2PE function does not support single-copy multicast/broadcast frame, which is important for services such as video and real-time broadcast; while the SME function decreases the efficiency of the network since every upstream frame is reflected downstream and a large portion of downstream bandwidth is wasted.

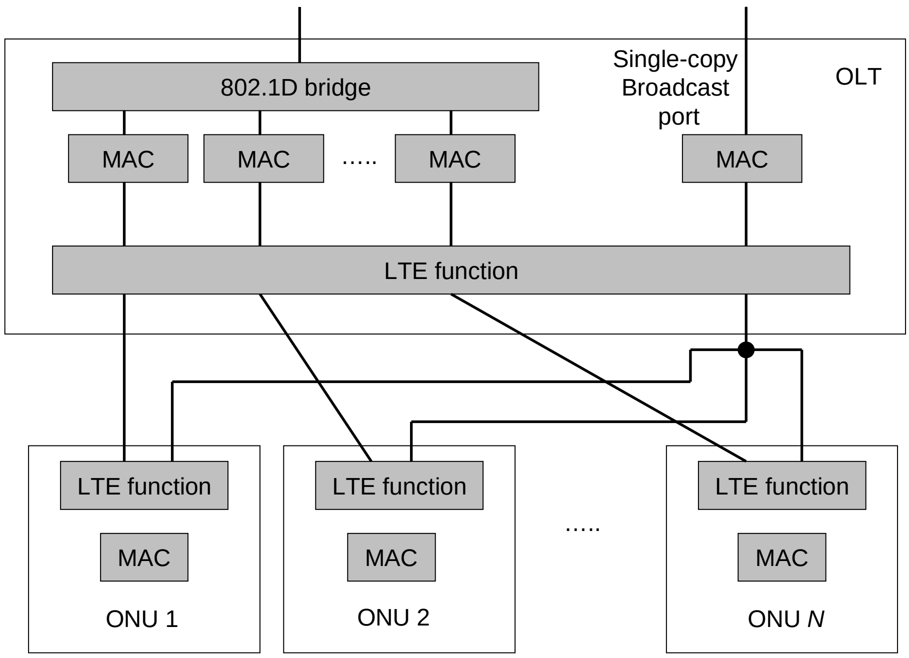

Fig. 2.11: Combination of P2PE and SME as the final solution [50].

As a consequence, the final solution appears to be combining the P2PE with a single copy broadcast MAC port as shown in Fig. 2.11. The OLT contains N+1 MACs, where N MACs are P2PE for each N ONU while one for broadcasting to all ONUs (single-copy broadcast channel). The single-copy broadcast channel is to be used for downstream broadcast only [60]. Therefore, only P2PE will be used for all upstream transmission; which also means that all upstream frames are required to be forwarded to the OLT Bridge. The bridging function in the OLT will decide to either forward the received frame from an ONU downstream back to the PON (inter ONU communication) or sending it to upper layer (network layer) and then to the Internet.

2.4. Long Reach and High Split-ratio PON

Higher split-ratios can increase the benefits of a PON by lowering cost through sharing OLT optics, electronic and feeder fibre among a larger number of users and more efficiently utilising the head end rack space for higher density OLT [61-63]. However, in providing such benefits to increase the split-ratio and distance of the PON, optical power budget remains a major challenge since increasing the split-ratio and distance could cause large amounts of attenuation and hence the system performance is compromised as the received signal power is reduced. Most of the previously proposed research works conducted studies on employing optical amplifiers to increase the power budget [64-76] while some studies were focusing on using forward error correction (FEC) technique to achieve higher split-ratios and longer reach within the network [77-81].

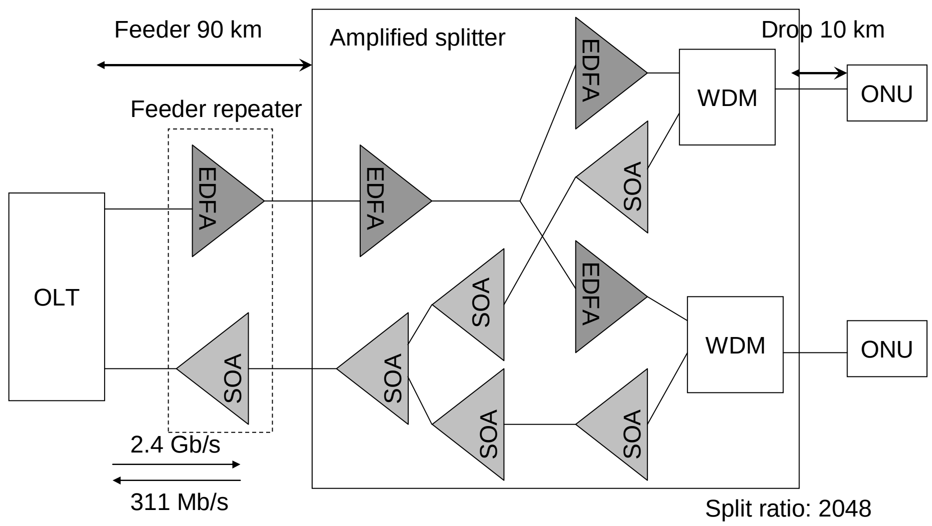

Fig. 2.12: The SuperPON architecture [64, 65].

As shown in Fig. 2.12, cascaded semiconductor optical amplifier (SOA) and Erbium-doped fibre amplifier (EDFA) has been used to extend PON reach to 100 km while supporting 2048 users as part of the SuperPON demonstration by the Advanced Communications and Technologies and Services (ACTS) project [64, 65]. The span consists of a maximum feeder length of 90 km and a drop section of 10 km while the optical amplifiers are hosted in the optical repeater units (ORUs), which are located at the intersection between the feeder and drop sections to compensate for the fibre and splitting ratio losses. The demonstration is based on asynchronous transfer mode (ATM) technology with a downstream bit rate of 2.5 Gb/s using TDM protocol and upstream bit rate of 311 Mb/s shared by all ONUs using TDMA protocol [64]. Although with major challenges of the SuperPON such as synchronisation for the optical amplifiers, monitoring and management of optical amplifiers at the ORUs as well as the support of burst mode transmission in the upstream direction; the SuperPON project has demonstrated the possibility and feasibility of constructing an extended reach and large number of users TDM-PON system using the SOA and EDFA based optical amplifiers [64, 65].

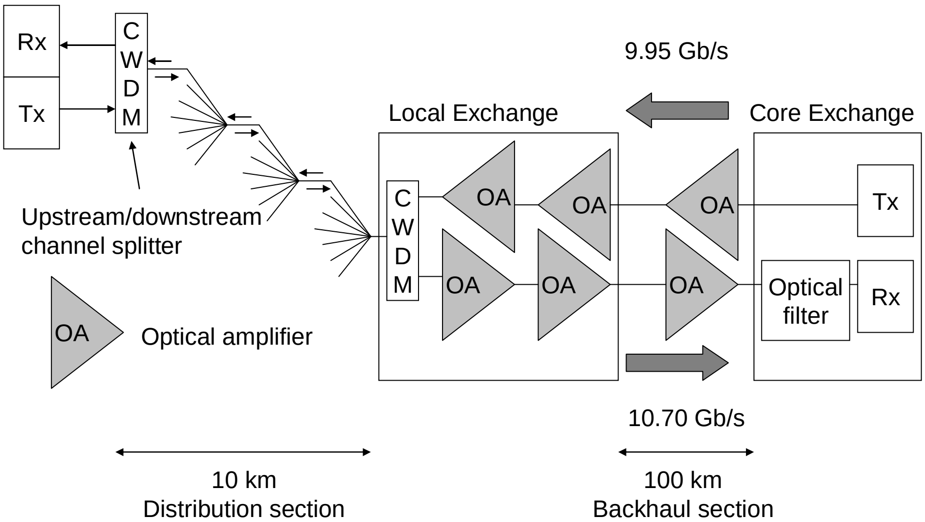

Fig. 2.13: British Telecom's long reach PON architecture [66].

In comparison to the SuperPON demonstration, British Telecom's Long-Reach PON has a reach of 100 km with a split-ratio of 1024 operating at a data rate of 10 Gb/s as shown in Fig. 2.13 [66]. Although the Long-Reach PON's optical split-ratio is only a half of that in the SuperPON, it only requires six optical amplifiers for both upstream and downstream operation as opposed to 39 required by SuperPON [76]. The long-reach PON was completely passive in the access network section between the customer premises and the local exchange site where intermediate amplification site was positioned immediately after the 1024-way split. This consideration is due to electrical power is already in placed at the local exchange and hence no electrical power must be installed in the distribution section. In addition, FEC technique and electronic dispersion compensation (EDC) are used in the demonstration as a substitute for optical dispersion compensating modules [66]. Nevertheless, technical challenges of the development of a low cost, 10 Gb/s burst mode transceivers at the ONU and OLT remains a critical issue [76].

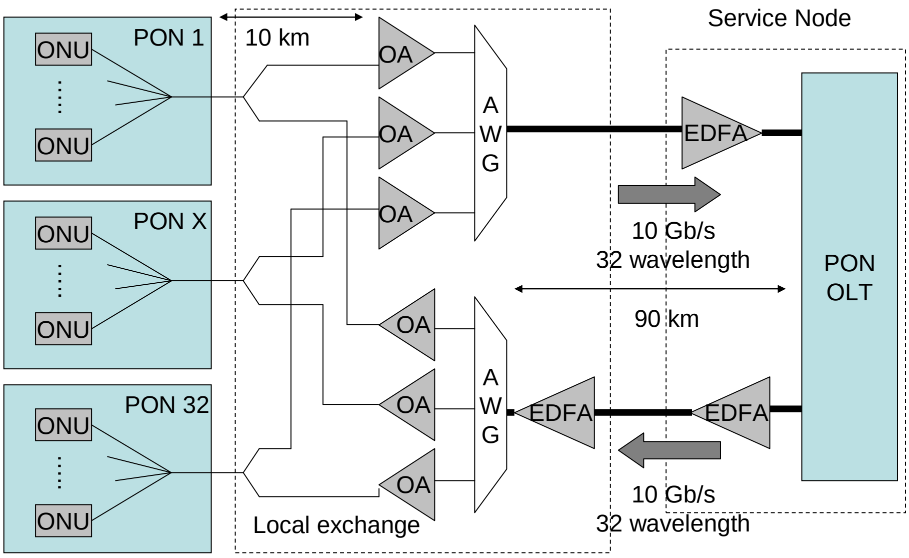

Fig. 2.14: PIEMAN hybrid WDM/TDM architecture [67].

To further increase the scalability of the access network, dense wavelength division multiplexing (DWDM) backhaul incorporating a 32 wavelength network with 100 km reach was demonstrated in the photonic integrated extended metro and access network (PIEMAN) project as shown in Fig. 2.14 [67]. Each of the 10 Gb/s 32 wavelength channels was uniquely allocated to a PON with a split-ratio of 512, enabling the network to support 16,384 (32 × 512) users with an average bandwidth of around 20 Mbps [69]. Colourless ONUs used in the project provides the benefit for each customer to buy an ONU without specifying the wavelength that is capable of selecting from 32 wavelengths with 50 GHz spacing [67]. By using DBA and colourless ONUs operating at 10 Gb/s, each user could burst at 10 Gb/s [69]. Furthermore, due to burst mode nature of the TDMA traffic in the upstream direction, standard EDFA is not appropriate due to their slow gain dynamics. This led to the solution of using an auxiliary wavelength that is adjusted relative to the transmitted upstream packet so that the optical power through the EDFA remains constant [69]. An alternative proposal based on hybrid DWDM-time division multiplexing (DWDM-TDM) was also used to demonstrate a long reach PON with the reach of up to 100 km, each working at different wavelengths to share the same fibre infrastructure [68]. This design demonstrated the combination of the extended reach of optically amplified PONs with the increased number of users enabled with DWDM.

In contrast to the use of optical amplifiers to amplify the optical signal power, FEC technique that is implemented in PON provides a coding gain of up to 7.8 dB at the BER of 10^{-10} by trading off a reduction in bandwidth due to overhead depending on receiver type [77]. However, most of the FEC techniques induce latency due to the requirement of adequate code blocks before decoding. Furthermore, this approach suffers from increased cost and power consumption of the OLT [61].

Furthermore, the use of optical amplification to extend the reach and split-ratio of the optical access network often leads to reduced cost-effectiveness and may not be applicable to network scenarios where average bandwidth expectations need not be very high or initial subscription rates may be too low to warrant such higher cost base. Since the cost of optical amplifiers is shared among the subscribers in the network, if the initial subscription rates become high, the use of optical amplifiers with higher operational costs will increase the subscription cost per user [82]. For these applications, a PON architecture incorporating a remote repeater was proposed to realise the cost-effective network with long reach and high split-ratios. This approach allows reduction in the cost of an ONU by using a low-cost vertical cavity surface emitting laser (VCSEL) based transmitters while extending the feeder fibre reach and split-ratio of the access system [83-86]. This scheme can be easily adopted in EPON and was demonstrated to support 256 number of users with 60 km reach, albeit with much smaller bandwidth per each user.

2.5. Bandwidth Assignment in EPON

In practise, an EPON system consists of an OLT and *N* ONUs where the distances between the OLT and each ONU are randomly distributed between 0.5 km to 20 km [50]. Downstream transmission is in continuous mode since all frames will arrive at each ONU before frame filtering based on LLID. However, the upstream transmission is in TDMA mode where the OLT will allocate timeslots for each ONU to transmit frames upstream based on the request message sent by the ONUs during the previous transmission cycle. Each ONU is required to send a REPORT message to the OLT in every transmission cycle to report its' queue status [50]. After receiving the REPORT message from all ONUs, the OLT will run the bandwidth assignment mechanism to fairly assign transmission timeslot for each ONU. Since the ONUs are not allowed to commence transmission at time intervals that are not allocated to them, timeslot assignment is essential to ensure fair bandwidth sharing among ONUs while maintaining high bandwidth utilisation efficiency. Various DBA schemes have been proposed to better utilise the upstream transmission [87-110]. Performance parameters such as average packet delay, average queue size, frame loss rate, and timeslot utilisation by ONUs are important matrixes in designing an efficient bandwidth assignment mechanism.

a) Average packet delay

   Ethernet packets arrive at the ONU at random times. Every packet has to wait for the next transmission timeslot to be transmitted upstream to the OLT. Therefore, the delay between the packet arrival and the beginning of the next timeslot is termed 'TDM delay' [50]. Due to bursty nature of the EPON traffic, some timeslots may be filled completely and some packets may be needed to be buffered even at light network load. These packets will have to wait for the later timeslots to be transmitted (may span multiple transmission cycles), which creates an additional delay called 'burst delay' [50]. These two parameters contribute the major packet delay results.

b) Average queue size

   For simplicity, most ONUs employ first-in-first-out (FIFO) buffer system. If the ONU is unable to transmit the packet due to limitation of timeslot assigned, the packet will be placed into the buffer. While taking packets out of the buffer, the ONU scheduler will select the packet that has spent the longest wait time in the buffer to be transmitted based on the FIFO rule. In order to reduce the cost of an ONU, smaller buffer size can be implemented. However, smaller buffer size represents a higher buffer overflow possibility which degrades the network efficiency as re-transmission of the lost packets is required. Therefore, the buffer behaviour in all ONUs in designing the bandwidth assignment methods remain an important element.

c) Frame loss ratio

As mentioned in part (a), burst traffic that causes burst delay is present even at light network load. This delay causes a large amount of packets to be buffered and the holding may span for multiple transmission cycles before being transmitted. While waiting for the next transmission cycle, incoming packets from the user ends will be continuous and this may result the buffers in the ONUs to be completely saturated especially during intermediate network load. Hence, incoming packets will be rejected and frame loss rate starts to increase. As a result, the three performance parameters of average packet delay, ONU queue size and frame loss ratio are linked with each other when designing the bandwidth assignment mechanism.

d) Timeslot utilisation

The REPORT message sent by each ONU only reports the buffer/queue size in the device without informing the OLT on the number of packets and their size. Since FIFO queue is used in most ONUs, if there is a packet that is currently at the head of the queue that does not fit in a partially occupied timeslot, this packet and all packets following it are needed to wait for the next timeslot. As a consequence, several packet scheduling methods have been proposed to allow some later arriving packets in the queue that are small enough to fit into the current timeslot to be transmitted [111-113].

2.5.1. Dynamic bandwidth assignment (DBA)

Bandwidth assignment model can be categorised into static bandwidth assignment (SBA) and dynamic bandwidth assignment modes. As shown in Fig. 2.15, the data rate of the access link from user groups to an ONU is represented by R_{user} Mb/s while the upstream transmission rate of an ONU to the OLT is represented as R_{ONU} Mb/s. For the SBA mode, the transmission cycle time, T_{cycle} is fixed and therefore, the R_{ONU} Mb/s available to each ONU in every transmission cycle is the same since the timeslot per ONU is constant at T_{cycle}/N regardless of the ONU offered load. However, due to bursty nature of the EPON traffic as discussed earlier in the section, some ONUs may be filled with many packets while other ONUs may have only a few packets to send. If SBA is used, same timeslot amount will be allocated to ONUs that have light traffic and to ONUs that have heavy traffic from end users; which directly increase the average packet delay in busy ONUs and more seriously increase the frame loss ratio. Furthermore, the average network throughput is decreased especially during intermediate and low network traffic load. As a consequence, various DBA algorithms [87-111] have been proposed to dynamically 1) assign the timeslot to each ONU where high offered load ONUs will be given longer upstream timeslot and low offered load ONUs will be assigned shorter timeslots and 2) set T_{cycle} to be variable since T_{cycle} equals the total timeslots for *N* ONUs. Among the various DBA algorithms, interleaved polling with adaptive cycle time (IPACT) appears to be the foundation of most DBA algorithms [50, 87].

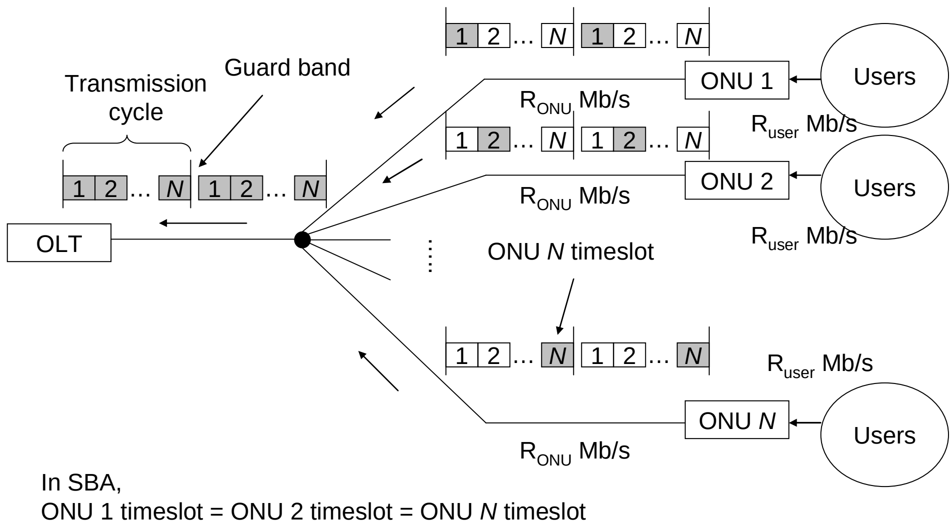

Fig. 2.15: Timeslot assignment using SBA mode.

The steps of an example polling algorithm in IPACT with three ONUs are shown in Fig. 2.16 [87]:

1) Assume that at a particular time, t_0, the OLT has constructed a polling table containing the information of how many bytes are stored in each ONU's buffer and RTT to each ONU based on GATE and REPORT messages discussed in previous section. At time t_0, the OLT sends a control GATE message to ONU1 to allow it to send 6000 bytes (Fig. 2.16 (a)).
2) Upon receiving the GATE message from the OLT, ONU1 starts sending its data upstream for a window size of 6000 bytes as in this example (Fig. 2.16 (b)). While the ONU is

transmitting packets upstream, the ONU keeps receiving packets from the end user groups. At the end of the transmission window, the ONU1 will generate a REPORT message containing the information of how many bytes left in its buffer (which is 550 bytes in this example).

3) Without waiting for the upstream data streams from ONU1 to arrive, the OLT is capable of sending a GATE message to ONU2 to notify its' transmission start time and timeslot size since the OLT contains the RTT information of all ONUs. Therefore, the OLT knows that the first bit will arrive exactly after the RTT associated to ONU1 expires and the time interval of the last bit will end based on the previously sent GATE message to ONU1. On top of all this information, the OLT is able to generate GATE messages for ONU2 before or while receiving data streams from ONU1. Please note that guard interval is included between upstream timeslots for AGC, CDR and time for the OLT to readjust its receiver sensitivity due to the reason that every ONU is located at a different distance and therefore the received power is different.
4) After certain period, the data from ONU1 arrives at the OLT. At the end of the data streams from ONU1, the OLT reads the REPORT message from the ONU and update the polling table regarding how many bytes remained in ONU1's buffer. By keeping track of times when GATE messages are sent out and first bid of the data is received, the OLT constantly updates the RTT entries for all ONUs.
5) Similar to steps 3 and 4, the OLT can calculate the time when the last bit from ONU2 will arrive to determine the transmission start time and timeslot size for ONU3 so that it will receive data streams from ONU3 after the last bit from ONU2. Again, the OLT will update its polling table upon receiving REPORT messages from ONU2 and ONU3 (Fig. 2.16 (d)).

In Fig. 2.16, the timeslot sizes granted by the OLT to ONU1, ONU2 and ONU3 are exactly what they were requesting. However, if an ONU contains high data volume, it could monopolise the entire bandwidth. In order to avoid this situation, the OLT will limit the maximum transmission size, which means every ONU will be allowed to send as many bytes as it requested, but no more than the maximum transmission window size. Nevertheless, setting the value for the maximum transmission window size is a challenge. Large maximum transmission window size will result in increased delay for all the packets, including real-time and high priority packets while small transmission window size will result in more bandwidth being wasted since the total guard time is increased as a result of increased number of timeslots [87]. Finally, researchers have found that 2 ms transmission cycle time, T_{cycle} (while maximum transmission window per ONU is T_{cycle}/N) is suitable for EPON with 16 ONUs due to voice traffic in the access network [87]. Two examples of grant scheduling services used in common OLT DBA agent are shown in Table 2.1.

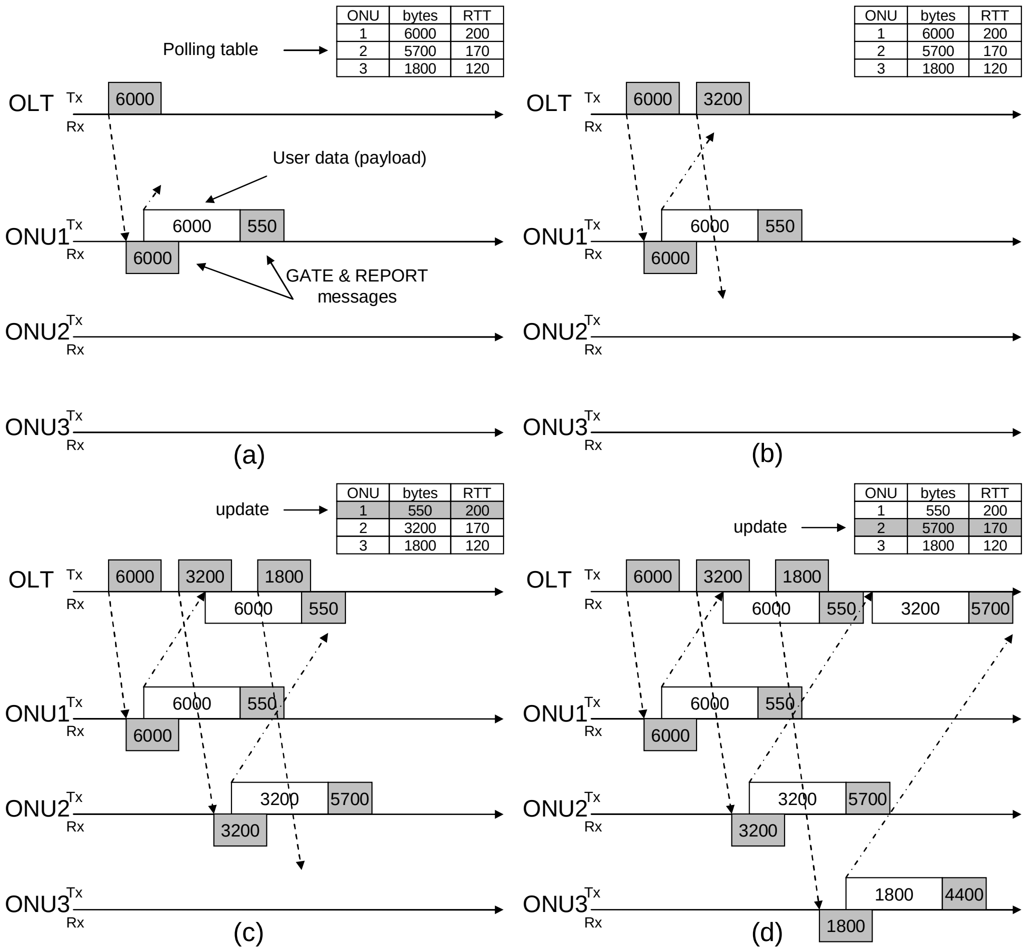

Fig. 2.16: Steps of IPACT algorithm [87].

Service Name	Formula	Description
Limited	$G\_DBA_{i,k} = \min \begin{cases} v_{i,k} \\ G^{\max} \end{cases}$	The OLT DBA agent will grant the requested number of bytes ($v_{i,k}$) to ONU *i* for transmission cycle *k* but no more than G^{max}.
Gated	$G\_DBA_{i,k} = v_{i,k}$	In this service, G^{max} is not used. Therefore, the OLT will grant the requested number of bytes ($v_{i,k}$) to ONU *i* in every transmission cycle. The only limiting factor in this service is the ONU buffer size since the ONU will not request more than the buffer size.

Table 2.1: Grant scheduling services used in DBA agent to determine ONU timeslot [50].

2.6. 10 Gb/s EPON Upgrade

The introduction of bandwidth intensive services and applications such as Internet protocol television (IPTV), video-on-demand (VoD), video conferencing and interactive gaming, which are enabled by gigabit-capable optical access networks, have been accepted by the subscribers with great enthusiasm and driven up the demand for higher bandwidth-intensive applications and services such as high-definition television (HDTV) that will consume 10 Mb/s per channel [114]. Therefore, the current IEEE 802.3ah 1 Gb/s symmetric EPON standard [49-48, 115], is only considered sufficient for a short period of time [114, 116].

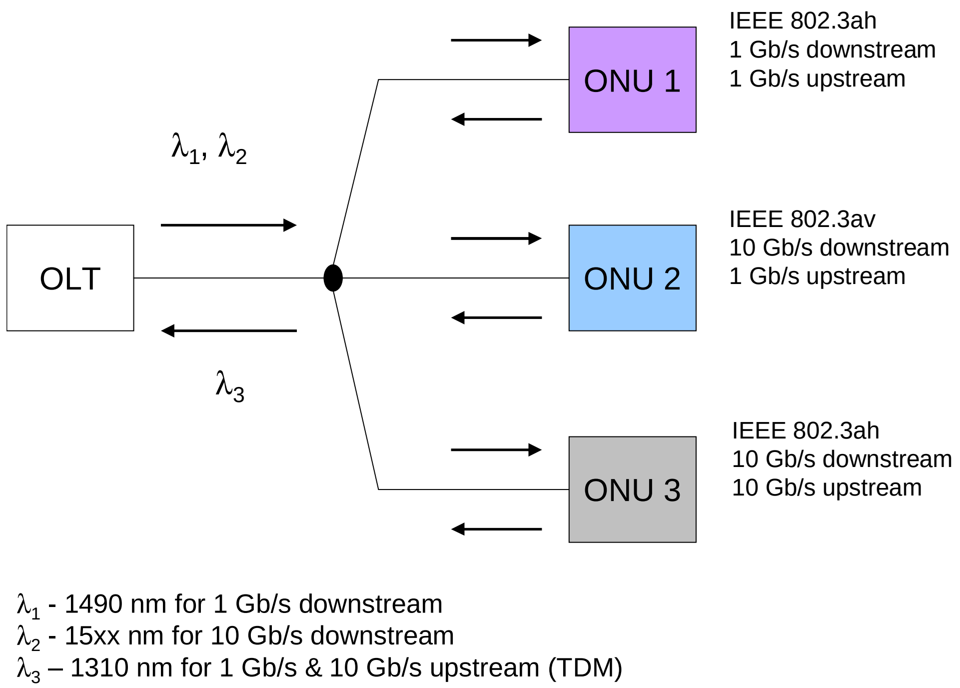

Fig. 2.17: Three possible steps for 10 Gb/s EPON system upgrade from conventional 1 Gb/s EPON system.

In year 2006, IEEE 802.3av Task Force was formed to standardise the 10G-EPON upgrade and it is completed in year 2009 [117-120]. As shown in Fig. 2.17, the upgrade of 10G-EPON will commence with the upgrade from symmetric 1G-EPON to asymmetric 10G downstream/1G upstream EPON before final the upgrade to symmetric 10G-EPON [116]. Therefore, the future 10 Gb/s EPON equipment must provide a gradual evolution path from the currently deployed 1 Gb/s symmetric EPON equipment, allowing in some cases for the coexistence of 1G-EPON and 10G-EPON. However, this gradual evolution towards symmetric 10G-EPON presents a number of technical challenges:

a) Wavelength allocation scheme

For complete backward compatibility between the 10G-EPON and 1G-EPON systems, the downstream 1Gb/s and 10 Gb/s data streams will be using different wavelengths (WDM) and hence creating two independent point-to-multipoint domains while the upstream 10 Gb/s and 1 Gb/s will be using the same wavelength channel at existing 1310 nm window. The current 1G-EPON downstream link will be using the existing 1490 nm wavelength channel while the wavelength channel of 1550 nm will be kept for video transmission as defined in IEEE 802.3ah standard [49]. Therefore, the only possible wavelength solution for 10 Gb/s downstream link will be an allocation between the 1575 nm - 1590 nm.

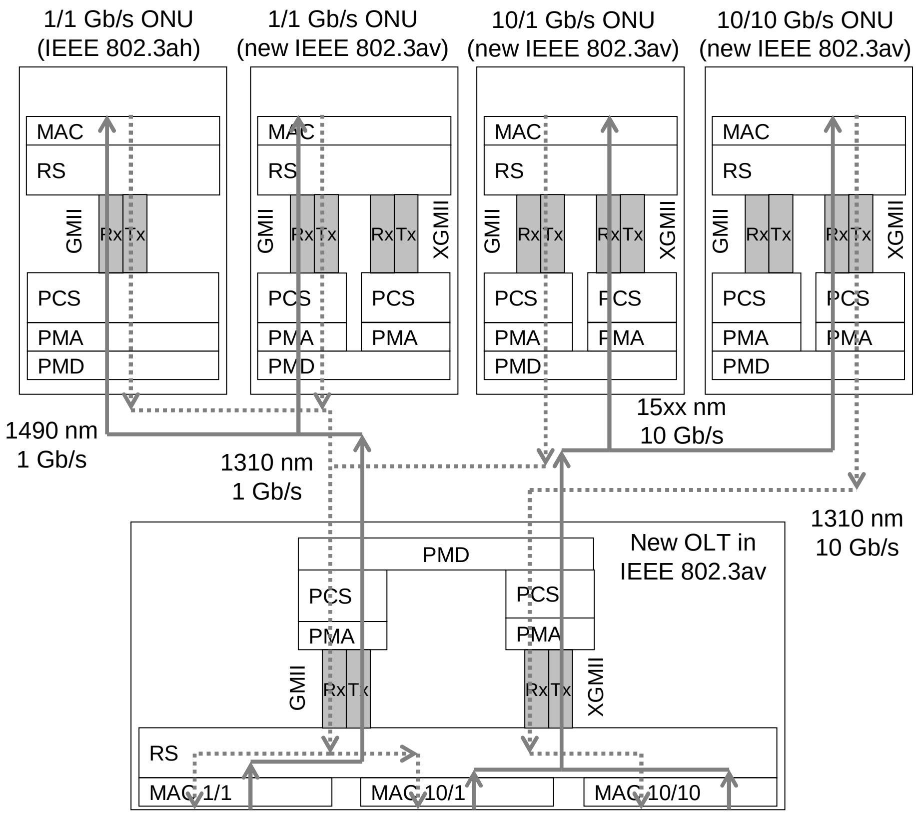

Fig. 2.18: OLT and ONU MAC stacks for 10/10 Gb/s symmetric ONU, 10/1 Gb/s asymmetric ONU, 1/1 Gb/s symmetric new ONU (IEEE 802.3av) and existing 1/1 Gb/s symmetric ONU (1EEE 802.3ah) [118].

b) Dual rate operation

Since the upstream transmission link of 1 Gb/s EPON and 10 Gb/s EPON will be using the same wavelength channel, this creates a critical challenge to design a burst mode receiver in the OLT that can detect the two transmission rates. Generally speaking, the data rate split can be performed in either optical domain or electronic domain [119]. Furthermore, the timing information derived from the DBA engine may have to be supplied to assist the fast data clock recovery and the precise and fair allocation of timeslots for three types of ONUs as shown in Fig. 2.17. Since the ONUs are blinded to any upstream transmissions originating from other ONUs in the network, all complexity of the dual rate operation will be concentrated in the OLT circuitry, allowing the ONU to implement only the necessary transmitter of the required version of stack and send the data streams in allocated timeslots assigned by the OLT [119]. Fig. 2.18 shows the detailed internal structure of a new dual rate OLT as well as the three types of ONU presented in Fig. 2.17.

c) Changes in MPCP framework

As discussed in section 2.3, MPCP is a protocol in EPON to manage the point-to-multipoint links. Since 1 Gb/s ONU and 10 Gb/s ONU will be coexisting in the same network at some time, modifications need to be done for MPCP messages used in 10G-EPON. The discovery GATE message is extended to carry one or two slots depending on whether the 10 Gb/s upstream capable ONUs are presented in the system, where each slot is allocated for a 1G or 10G discovery window or both simultaneously [121]. Furthremore, 10 Gb/s ONU must be capable of informing its transmission capabilities to the OLT through the extended REGISTER_REQ message in the new 10G-EPON system. Finally, when assigning multiple LLID addresses to an ONU, it is important for the OLT to make sure that the LLID addresses are having same data rate since it is impossible for an ONU to have LLID addresses linked to two different downstream data rates.

d) Other challenges

Since FEC is used in 1G-EPON, the 10G-EPON transmission links will be using the RS (255,233) code, which has better error correction abilities than the conventional FEC used in 1G-EPON. However, a better FEC code that uses more parity bit for error correction directly increases the transmission overhead. Therefore, several challenges to MPCP as well as the RS and PCS sub-layers (refer to section 2.3) are required to guarantee information integrity at all sub-layers [119]. On the other hand, the laser-on and off period that has been defined in 1G-EPON standard to be 512 ns and this has been found to be unrealistic for commercially available ONU transceivers [119]. Since there is no technical difference in terms of laser diodes and laser driver design between 1 Gb/s and 10 Gb/s devices, it is expected that the 10G-EPON PMD sub-layer will have similar parameter values compared to 1G-EPON [119].

2.7. Conclusion

This chapter presented a literature review of performance issues pertinent to this thesis in the current and next-generation optical access networks. A number of previously proposed solutions to independent services provisioning in WDM-PON have been discussed followed by introduction of SCM techniques, widely used for optical label swapping in optical switched networks. Despite disadvantages of SCM techniques in WDM-PON such as reduced extinction ratio of the data streams and the necessity of additional opto-electronic components, SCM technique has been proposed for independent services provision in WDM-PON system. The current TDM-PON standard of EPON has been presented in this chapter with detailed functions including EPON OSI layers, MPCP and logical topology issues. Since TDM-PON technology has been demonstrated as the most viable solution to address the access network bottleneck issue, several research topics have been conducted to increase the transmission distance and number of supporting users. Optical amplifiers, FEC technique and low cost repeater based solutions have been proposed to be utilised to improve the scalability of TDM-PON. When the network scales to support more users, bandwidth efficiency becomes essential in the access network. Section 2.5 has presented the basic details of bandwidth assignment mechanism used in current EPON system. The high bandwidth EPON that has been adopted by more and more users since the standardisation of the system has changed the users' ways of consuming network bandwidth from data and voice services to high bandwidth demand video services such as IPTV and HDTV. This has led to the new standardisation group to develop a new standard of 10 Gb/s EPON system to counter the bandwidth bottleneck issue in access system. In section 2.6, discussions on the technical challenges in deploying a new 10G-EPON have been carried out.

2.8. References

[1] A. Cook, J. Stern, "Optical fibre access-perspectives toward the 21st century," *IEEE Commun. Mag.*, vol. 32, no. 2, pp. 78-86, Feb. 1994.

[2] C.-H. Lee, W. V. Sorin, B. Y. Kim, "Fibre to the Home Using a PON Infrastructure," *IEEE J. Lightwave Technol.*, vol. 24, no. 12, pp. 4569-4583, Dec. 2006.

[3] C. Lin, K.-L. Deng, C.-K. Chan, "Broadband optical access networks," in *Proc. Laser and Electro-Optics Conference*, vol. 2, pp. 576-577, Jul. 2001.

[4] S. Vanhastel, R. Hernandez, "Enabling IPTV: What's Needed in the Access Network," *IEEE Commun. Mag.*, vol. 46, no. 8, pp. 90-95, Aug. 2008.

[5] A. Nikitin, V. Pyattaev, B. W. Kim, "Technological aspects of the triple play service on fixed access networks," in *Proc. 11th International Conference on Advanced Communication Technology*, vol. 3, pp. 1890-1893, Feb. 2009.

[6] T. Nakashima, Y. Hamazumi, N. Tokura, K. Kikuchi, "Photonic access network architecture," in *Proc. IEEE Global Telecommunications Conference*, vol. 1, pp. 602-606, 1991.

[7] Y. Mochida, "Technologies for local-access fibreing," *IEEE Commun. Mag.*, vol. 32, no. 2, pp. 64-73, Feb. 1994.

[8] T. H. Wood, "What architectures make sense for fibre access networks?," in *Proc. IEEE Annual Meeting of Laser and Electro-Optics Society*, vol. 2, pp. 122-123, Dec. 1998.

[9] P. Kourtessis, Y. Shachaf, C.-H., Chang, J. M. Senior, "PON topologies for dynamic optical access networks," in *Proc. 10th International Conference on Transparent Optical Networks*, vol. 4, pp. 131-134, Jun. 2008.

[10] D. W. Faulkner, D. B. Payne, J. R. Stern, J. W. Balance, "Optical networks for local loop applications," *IEEE J. Lightwave Technol.*, vol. 7, pp. 1741-1751, Nov. 1989.

[11] D. Kettler, H. Kafka, D. Spears, "Driving fibre to the home," *IEEE Commun. Mag.*, vol. 38, pp. 106-110, Nov. 1994.

[12] M. Shibutani, H. Ishikawa, H. Tezuka, W. Domon, M. Soda, K. Emura, "A gigabit-to-the-home (GTTH) system for future broadband access infrastructure," *IEEE International Conference on Communications*, vol. 2, pp. 1004-1008, 1997.

[13] N. J. Frigo, "Optical networking for local access," in *Proc. IEEE/LEOS Summer Topical Meetings in Advanced Applications of Lasers in Materials Processing, Broadband Optical Networks – Enabling Technologies and Applications, Smart pixels: Optical MEMS and their Applications*, pp. 39-40, Aug. 1996.

[14] N. J. Frigo, "Recent progress in optical access network," in *Proc. Optical Fibre Communication Conference*, pp. 142-143, Feb. 1996.

[15] S. Tang, Y. Ji, S. Cheng, "EPON upstream multiple access scheme," in *Proc. International Conference on Info-Tech and Info-Net*, vol. 2, pp. 273-278, Oct. 2001.

[16] R. D. Feldman, E. E. Harstead, S. Jiang, T. H. Wood, M. Zirngibl, "An evaluation of architectures incorporating wavelength division multiplexing for broad-band fibre access," *IEEE J. Lightwave Technol.*, vol. 16, no. 9, pp. 1546-1559, Sep. 1998.

[17] R. D. Feldman, T. H. Wood, J. P. Meester, R. F. Austin, "Broadband upgrade of an operating narrowband single-fibre passive optical network using coarse wavelength division multiplexing and subcarrier multiple access," *IEEE J. Lightwave Technol.*, vol. 16, no. 1, pp. 1-8, Jan. 1998.

[18] C.-J. Chae, E. Wong, R. S. Tucker, "Optical CSMA/CD media access scheme for Ethernet over passive optical network," *IEEE Photon. Technol. Lett.*, vol. 14, no. 5, pp. 711-713, May 2002.

[19] H. Frazier, G. Pesavento, "Ethernet takes on the first mile," *IT Professional*, vol. 3, no. 4, pp. 17-22, Jul. 2001.

[20] G. Maier, M. Martinelli, A. Pattavina, E. Salvadori, "Design and cost performance of the multistage WDM-PON access networks," *IEEE J. Lightwave Technol.*, vol. 18, no. 2, pp. 125-143, Feb. 2000.

[21] C. Dragone, "A N×N optical multiplexer using a planar arrangement of two star couplers," *IEEE Photon. Technol. Lett.*, vol. 3, no. 9, pp. 812-815, Sep. 1991.

[22] C. Dragone, C. A. Edwards, R. C. Kistler, "Integrated optics N×N multiplexer on silicon," *IEEE Photon. Technol. Lett.*, vol. 3, no. 10, pp. 896-899, Oct. 1991.

[23] H. Takahashi, K. Oda, H. Toba, Y. Inoue, "Transmission characteristics of arrayed waveguide N×N wavelength multiplexer," *IEEE J. Lightwave Technol.*, vol. 13, no. 3, pp. 447-455, Mar. 1995.

[24] M. K. Smit, C. Van Dam, "PHASAR-based WDM-devices: Principles, design and applications," *IEEE J. Select. Topics Quantum Electron.*, vol. 2, no. 2, pp. 236-250, Jun. 1996.

[25] G. Kramer, "What is Next for Ethernet PON?," in *Proc. 5th International Conference on Optical Internet and Next Generation Network*, pp. 49-54, Jul. 2006.

[26] IEEE P802.3 av task force, available online http://www.ieee802.org/3/av/

[27] R. Lin, "Next Generation PON in Emerging Networks," in *Proc. Optical Fibre Communication Conference*, pp. 1-3, Feb 2008.

[28] A. A. M. Saleh, J. M. Simmons, "Architectural principles of optical regional and metropolitan access networks," *IEEE J. Lightwave Technol.*, vol. 17, no. 12, pp. 2431-2448, Dec. 1999.

[29] A. Borghesani, "Optoelectronic Components for WDM-PON," in *Proc. 9th International Conference on Transparent Optical Networks*, vol. 1, pp. 305-308, Jul. 2007.

[30] A. F. F. Orlando, A. M. C. Soto, I. T. Monroy, "Optimizing the next generation optical access networks," in *Proc. IEEE Conference on Communications*, pp. 1-5, Sep. 2009.

[31] U. Hiblk, T. Saniter, F.-J. Westphal, "High capacity WDM overlay on a passive optical network," *IEE Electron. Lett.*, vol. 32, no. 23, pp. 2162-2163, Nov. 1996.

[32] P. P. Iannone, K. C. Reichmann, N. J. Frigo, "High-speed point-to-point and multiple broadcast services delivered over a WDM passive optical network," *IEEE Photon. Tech. Lett.*, vol. 10, no. 9, pp. 1328-1330, Sep. 1998.

[33] E. S. Son, K. H. Han, J. K. Kim, Y. C. Chung, "Bidirectional WDM passive optical network for simultaneous transmission of data and digital broadcast video service," *J. Lightwave. Tech.*, vol. 21, no. 8, pp. 1723-1727, Aug. 2003.

[34] J. Marti, J. Capmany, "Modeling optically prefiltered AM subcarrier multiplexed systems," *IEEE Transac. Microwave Theory and Techniques*, vol. 43, no. 9, pp. 2249-2256, Sep. 1995.

[35] J. Marti, J. Capmany, H. Mangharam, "Crosstalk analysis in optically prefiltered subcarrier multiplexed systems," *IEE Electron. Lett.*, vol. 29, no. 23, pp. 2054-2055, Nov. 1993.

[36] I. W. Winston, "Broadband Hybrid Fiber/Coax Access System Technologies (Telecommunications)," Academic Press, ISBN: 0127387552.

[37] Z. Zhu, V. J. Hernandez, M. Y. Jeon, J. Cao, Z. Pan, and S. J. B. Yoo, "RF photonics signal processing in subcarrier multiplexed optical-label switching communications systems," *J. Lightwave. Tech.*, vol. 21, no. 12, pp. 3155-3166, Dec. 2003.

[38] M. Y. Jeon, Z. Pan, J. Cao, S. J. B. Yoo, "BER performance of all-optical subcarrier label swapping with 2R regeneration," *IEEE Photon. Tech. Lett.*, vol. 16, no. 1, pp. 323-325, Jan. 2004.

[39] J. Yang, M. Y. Jeon, J. Cao, Z. Pan, S. J. B. Yoo, "Performance monitoring in transparent optical networks using self-monitoring optical-labels," *Electron. Lett.*, vol. 40, no. 21, pp. 1370-1372, Oct. 2004.

[40] M. Y. Jeon, Z. Pan, J. Cao, Y. Bansal, J. Taylor, Z. Wang, V. Akella, K. Okamoto, S. Kamei, J. Pan, S. J. B. Yoo, "Demonstration of all-optical packet switching routers with optical label swapping and 2R regeneration for scalable optical label switching network applications," *J. Lightwave. Tech.*, vol. 21, no. 11, pp. 2723-2733, Nov. 2003.

[41] D. Wolfson, A. Kloch, T. Fjelde, C. Janz, B. Dagens, M. Renaud, "40-Gb/s all-optical wavelength conversion, regeneration, and demultiplexing in an SOA-based all-active Mach-Zehnder interferometer," *IEEE Photon. Technol. Lett.*, vol. 12, no. 3, pp. 332-334, Mar. 2000.

[42] P. D. Sargis, R. E. Haigh, K. G. McCammon, S. Young, "Subcarrier multiplexing with dispersion reduction," *IEE Electron. Lett.*, vol 31, no. 20, pp. 1769-1770, 1995.

[43] P. D. Sargis, B. D. Henderer, M. E. Lowry, "10-Gb/s subcarrier multiplexed transmission over 490 km of ordinary single-mode fibre without dispersion compensation," *IEEE Photon. Tech. Lett.*, vol 9, no 12, pp. 1658-1660, Dec. 1997.

[44] J. Yu, G-K. Chang, A. Chowdhury, "Detecting Burst-Mode Optical Label or Payload Generated by OCSS Technique Using Conventional Receivers," *IEEE Photon. Tech. Lett.*, vol. 17, no. 7, pp. 1567-1569, 2005.

[45] A. Chowdhury, J. Yu, G.-K. Chang, "All-optical label swapping for same wavelength data switching using optical carrier suppression, separation and without regular wavelength converter," *IEEE Photon. Tech. Lett.*, vol. 17, no. 5, May 2005.

[46] J. Yu, G-K. Chang, "A Novel Technique for Optical Label and Payload Generation and Multiplexing Using Optical Carrier Suppression and Separation," *IEEE Photon. Tech. Lett.*, vol 16, no. 1, pp. 320-322, Jan. 2004.

[47] I. Cale, A. Salihovic, M. Ivekovic, "Gigabit Passive Optical Network – GPON," in *Proc. 29th International Conference on Information Technology Interfaces*, pp. 679-684, Jun. 2007.

[48] ITU-T recommendation G.894.1, "Gigabit-capable passive optical networks (GPON): General characteristics," Mar. 2008, available at: http://www.itu.int/rec/T-REC-G.984.1-200803-I/en.

[49] IEEE 802.3 ah EFM standard, (part of IEEE std 802.3), available online at http://standards.ieee.org/getieee802.

[50] G. Kramer, "Ethernet Passive Optical Networks," McGraw-Hill Professional, ISBN: 0071445625.

[51] G. Kramer, "10G-EPON: Drivers, Challenges and Solutions," in *Proc. 35th European Conference on Optical Communication*, 2009.

[52] W. W. Diab, H. M. Frazier, "Ethernet in the First Mile: Access for Everyone," IEEE Press (IEEE Standards Information Network), ISBN: 0738148385.

[53] M. Back, "Ethernet in the First Mile," McGraw-Hill Professional, ISBN: 007145506X.

[54] IEEE P802.1D Bridging standard (part of IEEE std 802.3), available online at http://standards.ieee.org/getieee802.

[55] D. Barnes, B. Sakandar, "Cisco LAN Switching Fundamentals," Cisco Press, ISBN: 1587058499.

[56] H. Suzuki, C. Easley, JC Kuo, A. Maislos, "EPON Compatibility with Peer-Peer, 802.1D Bridging, Pause Operation and Link Aggregation," electronic report available at: http://grouper.ieee.org/groups/802/3/efm/public/jul01/presentations/suzuki_2_0701.pdf.

[57] H. Suzuki, J. Song, O. Haran, G. Kramer, JC. Kuo, "EPON P2P Emulation Detail Behaviors – Basis for EPON protocol," electronic report available at: http://grouper.ieee.org/groups/802/3/efm/public/sep01/suzuki_2_0901.pdf.

[58] H. Suzuki, N. Finn, "EPON P2P Emulation and Shared Media Emulation For 802.1 compatibility," electronic report available at: http://grouper.ieee.org/groups/802/3/efm/public/nov01/suzuki_1_1101.pdf.

[59] H. Suzuki, O. Haran, "EPON P2P Emulation and Shared Media Emulation Layer Model and Behaviors," electronic report available at: http://grouper.ieee.org/groups/802/3/efm/public/jan02/suzuki_1_0102.pdf.

[60] H. Suzuki, A. Maislos, Y. Fujimoto, "EPON P2P Emulation and Downstream Broadcast Baseline Proposal," electronic report available at: http://grouper.ieee.org/groups/802/3/efm/public/mar02/suzuki_1_0302.pdf.

[61] H. Roberts, M. Rude, J. Solum, "Cost Effective High Split Ratios for EPON," presented at the *IEEE 802.3 Ethernet in the first mile study group*, Jul. 2001.

[62] P. D. Townsend, G. Talli, E. K. MacHale, C. Antony, "Long Reach PONs," in *Proc. 7th International Conference on Optical Internet*, pp. 1-2, Oct. 2008.

[63] I. Van de Voorde, C. M. Martin, J. Vandewege, and X. Z. Qiu, "The SuperPON Demonstrator: An Exploration of Possible Evolution Paths for Optical Access Networks," *IEEE Commun. Mag.*, vol. 38, no. 2, pp. 74-82, Feb. 2000.

[64] I. Van de Voorde, C. Martin, H. Slabbinck, L. Gouwy, B. Stubbe, X. Z. Qiu, J. Vandewege, P. Solina, "Evaluation of the super PON lab-demonstrator," in *Proc. 11th International Conference on Integrated Optics and Optical Fibre Communications and 23rd European Conference on Optical Communications*, vol. 3, pp. 331-334, Sep. 1997.

[65] C. Bouchat, C. Martin, E. Ringoot, M. Tassent, I. Van de Voorde, B. Stubbe, P. Vaes, X. Z. Qiu, J. Vandewege, "Evaluation of SuperPON demonstrator," in *Proc. LEOS Summer Topical Meetings on Electronic-Enhanced Optics, Optical Sensing in Semiconductor Manufacturing, Electro-Optics in Space, Broadband Optical Networks*, pp. IV25 – IV26, Jul. 2000.

[66] D. B. Payne and R. P. Davey, "The Future of Fibre Access Systems," *J. BT Tech.*, vol. 20, pp. 104-14, 2002.

[67] G. Talli, C. W. Chow, P. Townsend, R. Davey, T. De Ridder, X. Qiu, P. Ossieur, H. Krimmel, D. Smith, I. Lealman, A. Poustie, S. Randel, H. Rohde., "Integrated Metro and Access Network: PIEMAN," in *Proc. 12th European Conference on Networks and Optical Commununications*, pp. 493-500, 2007.

[68] G. Talli and P. D. Townsend, "Feasibility Demonstrator of 100 km long reach DWDM SuperPON with Upstream Bit Rates of 2.5 Gb/s and 10 Gb/s," in *Proc. Optical Fibre Communication Conference, OSA Technical Digest Series (Optical Society of America, 2005)*, paper OFI1, 2005.

[69] D. P. Shea, and J. E. Mitchell, "Long Reach Optical Access Technologies," *IEEE Networks Mag*. vol. 21, no. 5, pp. 5-11, Sep. 2007.

[70] I. T. Monroy, R. Kjaer, B. Palsdottir, A. M. J. Koonen, P. Jeppesen, "10 Gb/s bidirectional single fibre long reach PON link with distributed Raman amplification," in *Proc. European Conference on Optical Communications*, pp. 1-2, Sep. 2006.

[71] I. T. Monroy, F. Ohman, K. Yvind, R. Kjaer, C. Peucheret, A. M. J. Koonen, P. Jeppesen, "85 km Long Reach PON System Using a Reflective SOA-EA Modulator and Distributed Raman Fibre Amplification," in *Proc. IEEE Lasers and Electro-Optics Society*, pp. 705-706, Oct. 2006.

[72] K. Ennser, M. Zannin, S. Taccheo, "Extending reach of passive optical networks through optical amplification," in *Proc. International Conference on Transparent Optical Networks*, pp. 1-4, Jun. 2009.

[73] L. Spiekman, D. Piehler, P. Iannone, K. Reichmann, H.-H. Lee, "Semiconductor Optical Amplifier for FTTx," in *Proc. 9th International Conference on Transparent Optical Networks*, vol. 2, pp. 48-50, Jul. 2007.

[74] A. H. H. Tan, "SUPER PON-a fibre to the home cable network for CATV and POTS/ISDN/VOD as economical as a coaxial cable network," *IEEE J. Lightwave Technol.*, vol. 15, no. 2, pp. 213-218, Feb. 1997.

[75] G. Talli, C. W. Chow, E. K. MacHale, P. D. Townsend, "High Split Ratio 116km Reach Hybrid DWDM-TDM 10 Gb/s PON Employing R-ONUs," in *Proc. European Conference on Optical Communications*, pp. 1-3, Sep. 2006.

[76] C. Michie, T. Kelly, I. Andonovic, "Reflective Semiconductor Optical Amplifiers in passive optical networks," in *Proc. 14th OptoElectronics and Communications Conference*, pp. 1-2, Jul. 2009.

[77] X. Z. Qiu, Y. C. Yi, P. Ossieur, S. Verschuere, D. Verhulst, B. De Mulder, W. Chen, J. Bauwelinck, T. De Ridder, B. Baekelandt, C. Melange, J. Vandewege, "High performance burst-mode upstream transmission for next generation PONs," in *Proc. Asia Optical Fibre Communications and Optoelectronics Conference*, pp. 1-3, Oct. 2006.

[78] D. Nesset, R. P. Davey, D. Shea, P. Kirkpatrick, S. Q. Shang, M. Lobel, B. Christensen, "10 Gb/s bidirectional transmission in 1024-way split, 110 km reach, PON system using commercial transceiver modules, super FEC and EDC," in *Proc. 31st European Conference on Optical Communications*, pp. 135-138, 2005.

[79] D. Nesset, R. P. Davey, D. Shea, P. Kirkpatrick, S. Q. Shang, M. Lobel, B. Christensen, "10 Gb/s bidirectional transmission in 1024-way split, 110 km reach, PON system using commercial transceiver modules, super FEC and EDC," in *Proc. 31st European Conference on Optical Communication*, vol. 2, pp. 135-138, Sep. 2005.

[80] H. Lundqvist, G. Karlsson, “On error-correction coding for CDMA PON,” *IEEE J. Lightwave Technol.*, vol. 23, no. 8, pp. 2342-2351, Aug. 2005.

[81] C.-H. Yen, “An Efficient PCS to Transmit FEC-coded Frames in Ethernet PON,” in *Proc. International Symposium on High Capacity Optical Networks and Enabling Technologies*, pp. 245-250, Nov. 2008.

[82] P. Shea, J. E. Mitchell, “A 10-Gb/s 1024-Way-Split 100-km Long-Reach Optical-Access Network,” *J. Lightw. Tech.* Vol 25, 2007, pp. 685-693.

[83] V. Tran, C.-J. Chae, R. S. Tucker, “Low-cost and scalable passive optical network architecture using remote repeater,” *Electron*. *Lett*. vol. 42, no. 10, pp. 589-591, May 2006.

[84] A. V. Tran, C.-J. Chae, R. S. Tucker, “Cascadability performance of remote-repeater-based FTTP systems,” *Electron*. *Lett*. vol. 42, no. 24, pp. 1418-1420, Nov. 2006.

[85] A. V. Tran, C.-J. Chae, R. S. Tucker, “Cost-effective fibre-to-the-home system using remote repeater,” in *Proc. Optical Fibre Communication Conference*, OFC 2006, Mar. 2006.

[86] N. Nadarajah, A. V. Tran, C.-J. Chae, “10 Gb/s upgrade for high-split and long reach PON using remote repeater,” in Proc. Opto-Electronics and Communications Conf. (OECC/ACOFT ‘08), Jul. 2008.

[87] G. Kramer, B. Mukherjee, and G. Pesavento, “IPACT: A Dynamic protocol for an Ethernet PON (EPON),” *IEEE Commun. Mag.*, vol. 40, no. 2, pp. 74-80, Feb. 2002.

[88] C. M. Assi, Y. Ye, S. Dixit, M. A. Ali, “Dynamic Bandwidth Allocation for Quality-of-Service Over Ethernet PONs,” *IEEE J. Select. Areas Commun.*, vol. 21, pp. 1467-1477, Nov. 2003.

[89] S. Hwang, Z. D. Shyu, L. Y. Ke, C. C. Chang, “A novel early DBA mechanism with prediction-based fair excessive bandwidth allocation scheme in EPON,” *Computer Communications*, vol. 31, no. 9, pp. 1814-1823, Jun. 2008.

[90] M. P. McGarry, M. Reisslein, and M. Maier, “Ethernet Passive Optical Network Architectures and Dynamic Bandwidth Allocation Algorithms,” *IEEE Commun. Surveys and Tutorials*, vol. 10, no. 3, pp. 46-60, 2008.

[91] Shami, X. Bai, N. Ghani, C. M. Assi, H. T. Mouftah, “QoS Control Schemes for Two-Stage Ethernet Passive Optical Access Networks,” *IEEE J. Select. Areas Commun.*, vol. 23, no. 8, pp. 1467-1477, Aug. 2005.

[92] Y. Zhu, M. Ma, T. H. Cheng, “IPACT with Grant Estimation for EPON,” in *Proc. 10th IEEE Singapore International Conference on Communications systems*, pp. 1-5, Oct. 2006.

[93] M. Li, X. Fu, Y. Cao, F. Deng, “New dynamic bandwidth allocation algorithm for Ethernet PON,” in *Proc. 8th International Conference on Electronic Measurement and Instruments*, pp. 3-224-3-227, Jul. 2007.

[94] S.-H. Jang, J.-M. Kim, J.-W. Jang, “Performance evaluation of new DBA algorithm supporting fairness for EPON,” in *Proc. IEEE Region 10 Conference TENCON*, vol. 3, pp. 29-32, Nov. 2004.

[95] T. Fan, H. T. Mouftah, “A Qos-Based Dynamic Bandwidth Allocation Algorithm for EPONs,” in *Proc. 23rd Biennial Symposium on Communications*, pp. 140-143, 2006.

[96] B. Skubic, J. Chen, J. Ahmed, L. Wosinska, B. Mukherjee, “A comparison of dynamic bandwidth allocation for epon, gpon, and next-generation tdm pon – [topics in optical communications],” *IEEE Commun. Mag.*, vol. 47, no. 3, pp. S40-S48, Mar. 2009.

[97] W.-P. Chen, S.-W. Kau, B.-Y. Liao, W.-S. Hwang, W.-T. Hu, “A Sort-Based DBA Algorithm for EPON System,” in *Proc. 8th International Conference on Intelligent Systems Design and Applications*, vol. 2, pp. 223-228, Nov. 2008.

[98] J. Zheng, “Efficient bandwidth allocation algorithm for Ethernet passive optical networks,” in *Proc. IEE Communications*, vol. 153, no. 3, pp. 464-468, Jun. 2006.

[99] Y. Qiu, “A novel DBA algorithm with QoS support for EPON networks,” in *Proc. 2nd IEEE International Conference on Broadband Network & Multimedia Technology*, pp. 414-417, Oct. 2009.

[100] I-S. Hwang, Z.-D. Shyu, J.-Y. Lee, “A QoS-based DBA mechanism in EPON,” in *Proc. 7th International Conference on Optical Internet*, pp. 1-2, Oct. 2008.

[101] W. Chen, J. Song, J. Leng, H. Lu, “A New Double Scheduling DBA Algorithm for Next Generation Access Network,” in *Proc. 8th International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing*, vol. 2, pp. 673-678, Jul. 2007.

[102] H. Miyoshi, T. Inoue, K. Yamashita, “QoS-aware dynamic bandwidth allocation scheme in Gigabit-Ethernet passive optical networks,” in *Proc. IEEE International Conference on Communications*, vol. 1, pp. 90-94, Jun. 2004.

[103] X. Chen, M. Yu, Y. Zhang, Y. Deng, “A novel upstream dynamic bandwidth assignment for Ethernet PONs,” in *Proc. International Conference on Communication Technology Proceedings*, vol. 1, pp. 748-750, Apr. 2003.

[104] H. Ikeda, K. Kitayama, “Dynamic Bandwidth Allocation With Adaptive Polling Cycle for Maximized TCP Throughput in 10G-EPON,” *IEEE J. Lightwave Technol.*, vol. 27, no. 23, pp. 5508-5516, Dec. 2009.

[105] J. Hwang, M. Yoo, “QoS-aware class gated DBA algorithm for the EPON system,” in *Proc. International Conference on Advanced Technologies for Communications*, pp. 363-366, Oct. 2008.

[106] C.-H. Chen, H.-T. Wu, K.-W. Ke, “Predictive Credit Based Dynamic Bandwidth Allocation Mechanism in Ethernet Passive Optical Network,” in *Proc. IEEE Region 10 Conference*, pp. 1-4, Nov. 2006.

[107] C. G. Park, H. S. Jung, D. H. Han, Y. Lee, “Performance analysis of DBA scheme with interleaved polling algorithm in an Ethernet PON,” in *Proc. 9th International Symposium on Computers and Communications*, vol. 2, pp. 792-797, Jun. 2004.

[108] G. Chen, D. Fan, Z. Wei, Y. Fang, Y. Qiao, “High Performance of Fair Bandwidth Allocation Algorithm for an Ethernet PON,” in *Proc. International Nano-Optoelectronics Workshop*, pp. 256-257, Jul. 2007.

[109] J. Zheng, S. Zheng, “Dynamic Bandwidth Allocation with High Efficiency for EPONs,” in *Proc. IEEE International Conference on Communications*, vol. 6, pp. 2699-2703, Jun. 2006.

[110] D.-Y. Lee, S.-H. Oh, “A new DBA scheme to improve bandwidth utilization in EPONs,” in *Proc. 8th International Conference on Advanced Communication Technology*, vol. 2, pp. 1063-1067, Feb. 2006.

[111] M. R. Radivojevic, P. S. Matavulj, “Implementation of Intra-ONU Scheduling for Quality of Service Support in Ethernet Passive Optical Networks,” *IEEE. J. Lightwave Technol.*, vol. 27, no. 18, pp. 4055-4062, Sep. 2009.

[112] G. Kramer, A. Banerjee, N. K. Singhal, B. Mukherjee, S. Dixit, Y. Ye, “Fair queuing with envelopes (FQSE): a cousin-fair hierarchical scheduler for subscriber access networks,” *IEEE J. Select. Areas in Commun.*, vol. 22, no. 8, pp. 1497 – 1513, Oct. 2004.

[113] N. Ghani, A. Shami, C. Assi, M. Y. A. Raja, "Intra-ONU bandwidth scheduling in Ethernet passive optical networks," *IEEE Commun. Lett.*, vol 8, no. 11, pp. 683-685, Nov. 2004.

[114] G. Kramer, "What is Next for Ethernet PON?," in *Proc. 5th Int'l. Conf. Optical Internet and Next Generation Network*, pp. 49-54, Jul. 2006.

[115] G. Kramer, G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," *IEEE Commun. Mag*. vol. 40, no. 2, pp. 66-73, Feb. 2002.

[116] M. Hajduczenia, H. J. A. da Silva, P. p. Monteiro, "Development of 10 Gb/s EPON in IEEE 802.3av," *IEEE Commun. Mag.*, vol 46, no. 7, pp. 40-47, July 2008.

[117] R. Lin, "Next Generation PON in Emerging Networks," in *Optical Fibre Communication Conference*, pp. 1-3, Feb. 2008.

[118] IEEE P802.3 av task force, available online http://www.ieee802.org/3/av/

[119] M. Hajduczania, H. J. A. da Silva, "Next generation PON systems – Current status," in *Proc. 11th Int'l Conf. Transparent Optical Networks*, pp. 1-8, Jun. 2009.

[120] C. Chen, Z. Chair, B. Velmurugan, "10G EPON: Next generation Ethernet passive optical networks," in *Proc. Optical Fibre Communication Conference*, Mar. 2009.

[121] M. Hajduczenia, H. J. A. da Silva, N. Borges, "Discovery Process for Emerging 10 Gb/s EPONs," *IEEE Commun. Mag.*, vol 46, no 11, pp. 82-90, November 2008.

3 Independent Services Provisioning in WDM-PON

3.1. Introduction

Wavelength division multiplexed passive optical networks (WDM-PON) technology has been recognised as one of the most suitable solutions for bandwidth bottleneck in the last mile due to its virtual point to point connection between the service providers and customers. This solution becomes ideal for access networks when further important benefits are included, such as network security, simple management and upgradeability as discussed in Chapter 2 [1-3]. However, these advantages of WDM-PON can diminish when it is used for provision of additional independent services such as broadcast video. Several solutions can be utilised if two independent services such as video or another such independent service has to be overlaid onto the WDM-PON. One is an additional set of wavelengths separated by the free-spectral-range (FSR) of the arrayed waveguide grating (AWG) such as a technique proposed by the Institute for Communication Technology of Braunschweig Technical University on the delivery of broadcast video services on different wavelength channels described in [4]. Several similar techniques have also been proposed by using the WDM overlay on PON or broadband light emitting diode (LED) for the delivering of broadcast channels [5-6]. Nevertheless, out of these two proposals, the first technique requires a large number of WDM filters and couplers while the second technique requires a pair of fibres with frequency up/down-conversion of video signals due to the limited modulation bandwidth of LED [5-6]. Furthermore, some researchers have suggested the use of time division multiplexed (TDM) support components at the central office's (CO) optical line terminal (OLT) and every optical network unit (ONU) in order to insert and extract different service traffic streams from the same wavelength [7]. These proposed techniques can also be complicated and costly to implement especially when the two independent services are delivered by different service providers.

In this chapter, a simple scheme that uses single wavelength and modulator to generate two optical channels to carry two independent high speed data streams will be discussed where one signal is transmitted as a baseband signal and the other as a low frequency subcarrier signal. They are optically separated by a colourless periodic filter at the ONU and both channels are detected with conventional baseband receivers. These two channels are fixed and closely separated in frequency and can pass through the narrowband filters such as the AWG and changes in wavelength stability will cause no effect to the data streams. This technique solves the complication of independent service delivery by different service providers on the same wavelength without TDM schemes. For example, the service provider that owns the infrastructure can easily lease the additional independent channel to another service provider without any complications in cost and revenue calculations. However, it is noted that when the additional services consist of analogue and digital television services; it may require increased performance requirements for the laser transmitter in terms of power and linearity.

The chapter is organised as follows. Section 3.2 describes the proposal of independent services provisioning in WDM-PON system using single laser, modulator and passive periodic filter at the ONUs, followed by the experimental demonstration of the scheme. Section 3.3 presents the results to prove the feasibility of the proposed scheme followed by the performance analysis with different carrier-to-subcarrier (CSR) power ratio in the signals. Section 3.4 discusses the crosstalk effect from subcarrier channel on the baseband channel. Finally, section 3.5 summarises the overall chapter.

3.2. Independent Services Provisioning in WDM-PON

As discussed previously in Chapter 2, subcarrier multiplexing technique in optical domain has been studied by [8] and [9] for crosstalk analysis before the technique was utilised to generate relatively low speed additional data channels such as control signals or labels in label switching networks [10-13] and also in multiple channel generation that uses high frequency subcarrier signals [14, 15]. Also, technique such as the optical carrier suppression and separation (OCSS) has been proposed to carry payload and label information on an optical carrier [16-18]. The proposed scheme in this chapter electrically combines two independent high speed data streams, one as a baseband signal and the other as a low frequency subcarrier signal. After transmission, the signal is passed through a colourless (same device at all ONUs) periodic filter that optically separates the signals at each ONU. This enables separate conventional baseband receivers to be used in detection of the independent data streams providing a simple scheme for provision of independent services.

3.2.1. Demonstration of the scheme for provisioning of independent services in WDM-PON

A series of experiments were carried out to demonstrate the proposed scheme. As shown in Fig. 3.1, an optical carrier from a tunable laser was modulated using a Mach-Zehnder Modulator (MZM) with two independent $2^{31} - 1$ pseudorandom binary sequence (PRBS) non-return zero (NRZ) baseband data streams at 1.5 Gb/s; one as a baseband signal and the other as a subcarrier signal at 6 GHz in amplitude shifted keying (ASK) format. At the radio frequency (RF) front end, a MITEQ DM0520LW1 mixer is used to mix the 6 GHz RF signal with 1.5 Gb/s data stream (as channel 1). A HP11667A power splitter is then used to combine channel 1 with another baseband data stream (channel 2) before optical modulation. These two channels are then modulated using a Lucent X2623CS MZM with half wave voltage, V_π of ~3V. The modulated optical signal was transmitted through a 20 km standard single mode fibre (SMF) without dispersion compensation, and a 100 GHz AWG is used to separate the WDM channels. The launch optical power into the fibre for each composite signal was -2 dBm.

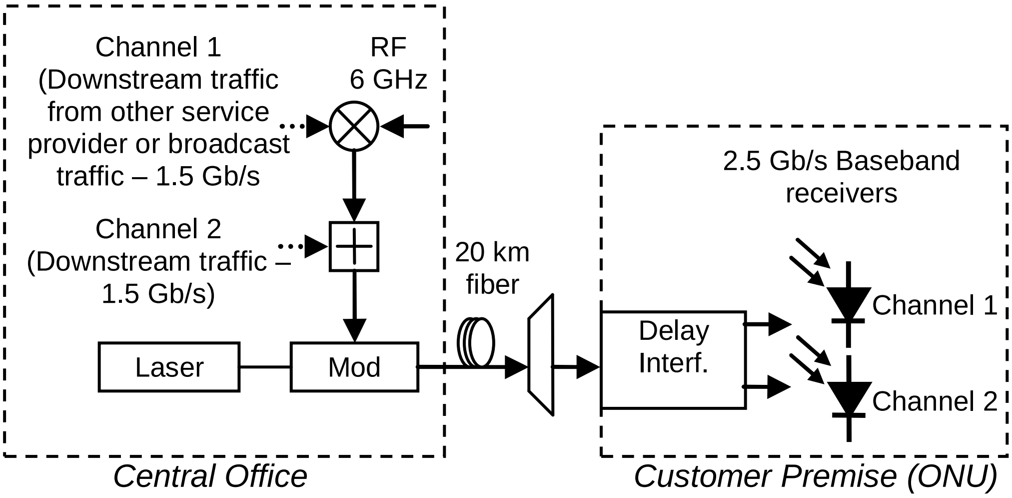

Fig. 3.1: Experiment to demonstrate provision of independent services in WDM-PON.

At the ONU, the optical signal was passed through a delay interferometer, DI (a 100 ps differential phase shift keying, DPSK demodulator) with a 100 ps differential delay, 10 GHz FSR and 5.3 GHz electrical 3 dB bandwidth in each pass-band; which acts as the simple colourless periodic filter. Ideally a 5 GHz subcarrier should be selected for a 100 ps DI (which is at the centre of the 10 GHz bandwidth). However we have discovered through simulations as presented in the following sections, that one can use a subcarrier frequency of up to 7 GHz without any significant penalty (assuming ideal carrier wavelength alignment with the DI pass-band). Therefore, a 6 GHz subcarrier is used to reduce the electrical interference between the two data streams after the mixer stage as no RF filters were used in the experiment. However, a 5 GHz subcarrier should be used to give best stability response in a practical implementation. Although currently DI can be relatively expensive component to be installed in the ONU with sensitivity temperature, economies of scale due to mass production in the future may reduce the cost of the DI and a thermal packaging for practical deployment.

The DI optically separated the signal into the two output arms that enable baseband detection of the two independent data streams using two standard 2.5 Gb/s PIN receivers. After photo-detection, an RF amplifier with a 3-dB bandwidth of 2.5 GHz was used for signal amplification while no additional RF filters were used. In practice, the DI can be temperature tuned by a current/voltage signal to achieve the desired initial phase accurately. The experiment was repeated for three adjacent wavelength channels separated by 100 GHz.

3.3. Results

A series of results have been obtained from experiments and simulations. In this section, the optical spectra for three different wavelengths will be discussed first. Consequently, the analysis of the 100 ps DI frequency response will be carried out followed by the bit-error-rate (BER) analysis of the proposed scheme. Then, the eye diagrams from both experiments and simulations will be discussed. Finally, the impacts of different CSR in the proposed scheme will be presented.

3.3.1. Optical spectra

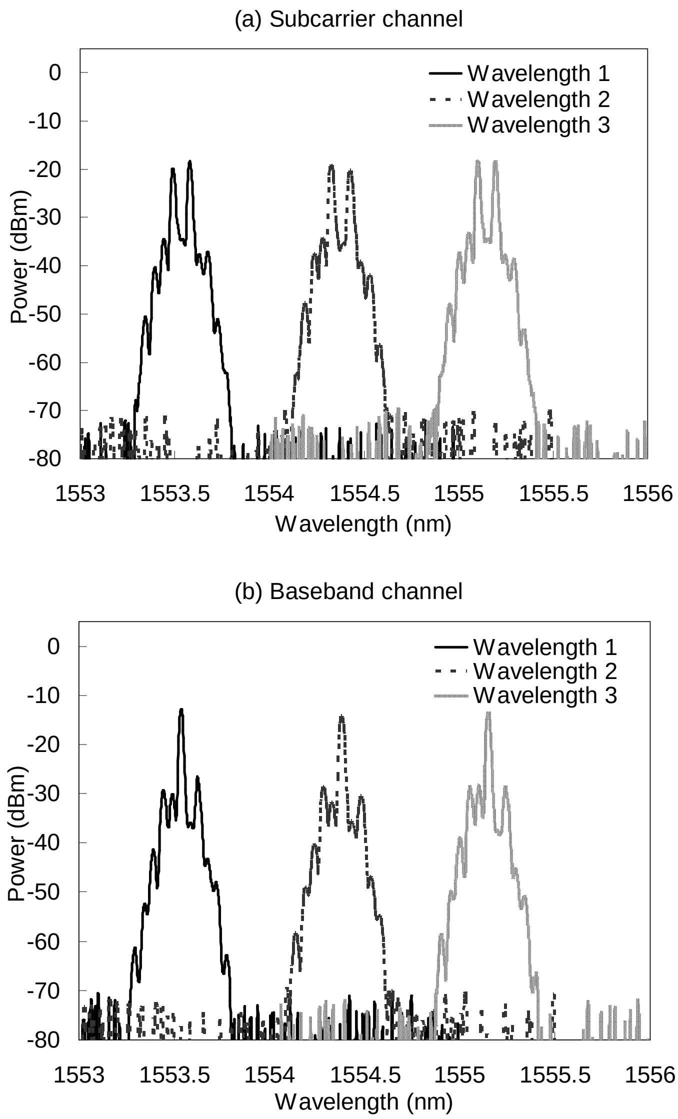

Fig. 3.2: Optical spectra for three different wavelengths of 1553.55 nm, 1554.38 nm and 1555.16 nm showing (a) the subcarrier and (b) the baseband channels.

The optical spectra of the modulated optical signal at the two output arms of the DI are shown in Fig. 3.2. The separated signal on the subcarrier is shown in Fig. 3.2 (a) and Fig. 3.2 (b) shows the separated signal on the baseband, both carrying 1.5 Gb/s independent data streams. The wavelengths used were 1553.55 nm, 1554.38 nm and 1555.16 nm. The separation between these two wavelengths is around 0.8 nm, which is equivalent to 100 GHz to resemble International Telecommunication Union (ITU) grid. These three wavelengths are separated by the AWG with a channel separation of 100 GHz.

3.3.2. DI frequency response

The frequency response for data on a 5 GHz subcarrier signal for a 100 ps DI is given below. Similar performance is observed for the baseband signal. We observe a 3 dB electrical bandwidth (single side band) of 2.65 GHz.

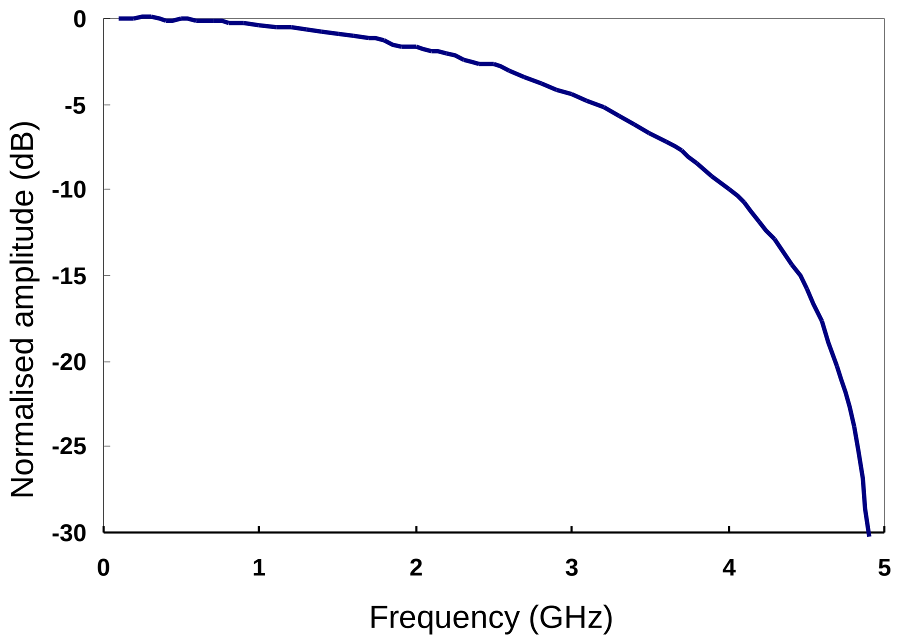

Fig 3.3: Frequency response for the 100 ps DI.

Initially, the wavelength in the PON needs to be selected to match the DI passbands. Misalignment of the wavelength with the DI can affect the performance of both channels. Therefore, detailed simulations using commercial software has been carried out to quantify the wavelength mismatch tolerance. The normalised power penalty when the wavelength is detuned from the ideal setting for both channels are shown Fig. 3.4. The power is measured before the DI and hence shows the penalty in the required transmission power to obtain a BER of 10^{-9}. The results are for a 50 ps DI with 10 GHz subcarrier, which we believe is the suitable device to use in practical implementation.

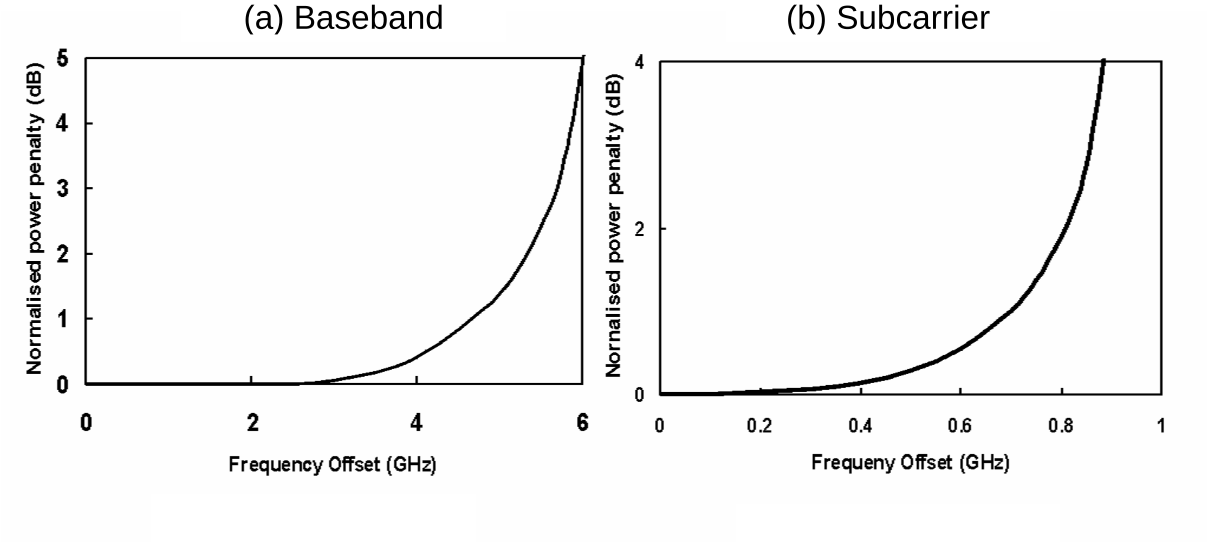

Fig 3.4: Normalised power penalty vs frequency detuning of the laser for (a) baseband channel and (b) the subcarrier channel.

If the wavelength detuning range is defined as the 3 dB penalty margin, approximately 11.4 GHz and 1.7 GHz were obtained for the baseband and subcarrier channels respectively. The subcarrier channel is more sensitive to wavelength mismatch as the relative power change in this channel is larger with deviation of the pass-band. Also as the wavelength deviates from the ideal alignment, more power from the larger power baseband channel leaks into the subcarrier channel giving a significant penalty. There is a much larger tolerance range for the downstream signal and it is almost immune to wavelength deviation until the channel goes off the pass-band of the DI. This required wavelength tolerance can be achieved by tuning of the DI. The DI is an all-fibre Mach-Zehnder interferometer with a heater element designed to have direct contact with the optical fibre to allow tuning of the unit to the desired phase with higher accuracy and a 10 kΩ thermistor is provided for fibre temperature measurement. The fibre heater can be used by either current/voltage or temperature control.

The corresponding simulations for a 100 ps DI as used in experiment gives a detuning range of 0.7 GHz for the subcarrier signal and 5.6 GHz for the baseband signal.

3.3.3. Bit-error-rate analysis

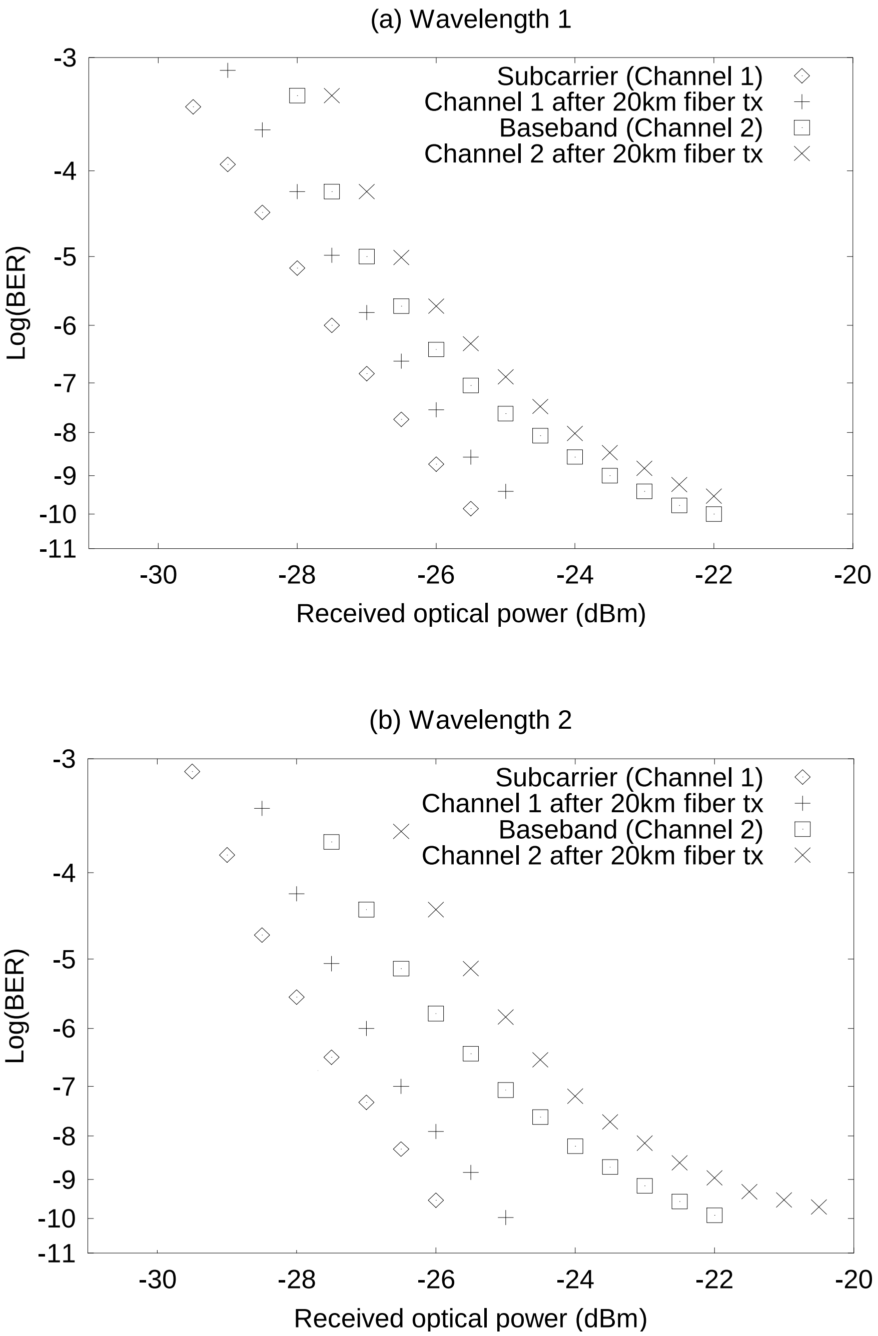

Fig. 3.5: BER measurements for two adjacent wavelength channels before and after 20 km fibre transmission with CSR of 11 dB, where (a) is at 1553.55 nm and (b) is at 1554.38 nm.

The BER measurements for the two 100 GHz separated wavelengths each carrying two 1.5 Gb/s independent channels separated at 6 GHz subcarrier frequency before and after 20 km fibre transmission are shown in Fig. 3.5. The optical power in the figure is measured after the DI. From the figures, around 0.5 dB power penalty is observed after transmission for both wavelengths measured. This difference in sensitivity may be due to back-reflected light in fibre transmission and at connectors. It is noted that the BER curves and sensitivity are different for both channels. When a subcarrier signal is intensity modulated onto an optical carrier, spectral components are created on the carrier. If the total signal is detected without optical filtering, only the spectral component that is modulated on the subcarrier signal will appear in the detected electrical signal [19, 20]. However, a low amplitude inverted copy of the data stream modulated on the subcarrier appears when the subcarrier signal is optically separated (where this phenomenon will be explained in section 3.4). This leads to crosstalk in the baseband channel from the subcarrier channel giving the slow roll off in BER curve. However, this can be reduced by decreasing the amplitude of the RF signal into the modulator. On the other hand, the separated subcarrier signal does not suffer this crosstalk from the other channel after filtering and is mainly limited by standard noise mechanisms such as thermal noise and hence a typical slope for BER curve was obtained.

3.3.4. Eye diagram analysis

Eye diagrams are a very simple way of quickly assessing the quality of a digital signal. A constructed eye contains every possible bit sequence from simple 101's and 010's, through to isolated ones after long runs of consecutive zeros and other problem sequences, that often show up weaknesses present in system design [21]. Here in this sub-section, the eye diagrams of baseband and subcarrier channels will be analysed based on experimental and simulation results.

The eye diagrams for the baseband and subcarrier channels are shown in Fig. 3.6 and Fig. 3.7 respectively. The eye diagrams as shown in both figures were taken during the experiment at relatively high received optical power around -22 dBm and CSR of 11 dB, which means at very low level of crosstalk from subcarrier channel. By comparing both figures, it is clearly shown that there is some broadening at the zero level of the baseband channel's eye compared to the subcarrier channel's eye pattern in Fig. 3.6. Although this observation is not obvious due to the eye diagrams being taken in error-free region, it does depict some crosstalk effect from subcarrier channel on the baseband channel.

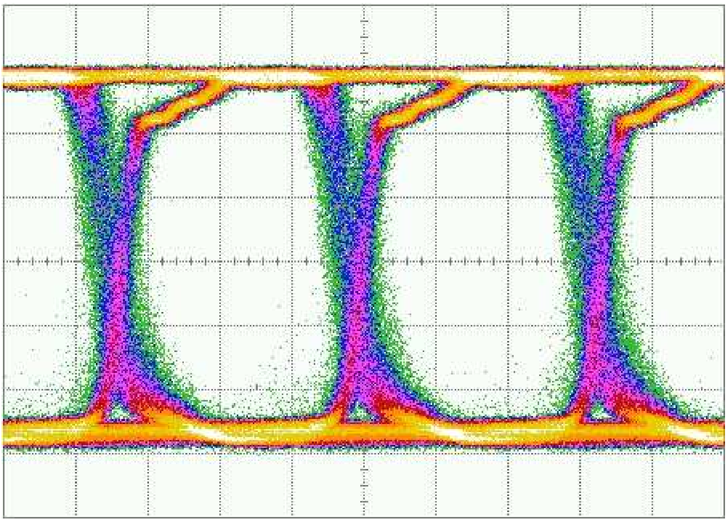

Fig.3.6: Baseband channel eye pattern at CSR of 11 dB.

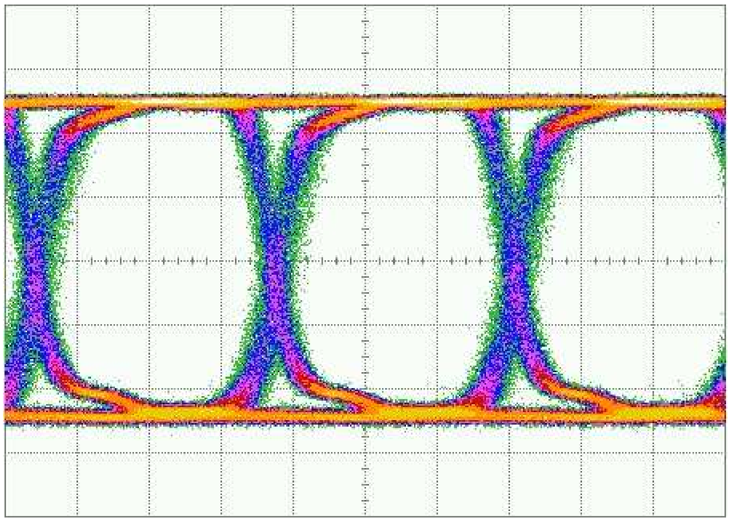

Fig. 3.7: Subcarrier channel eye pattern at CSR of 11 dB.

To further analyse the subcarrier crosstalk effect on baseband channel, simulations have been carried out. The eye patterns for the (a) baseband channel and (b) the subcarrier channel are shown in Fig. 3.8 respectively, where the data streams for both channels are synchronised. In parallel, Fig. 3.9 shows the eye patterns for the (a) baseband channel and (b) the subcarrier channel with independent data stream (neither correlated nor synchronised as in experiments).

As observed, both figures show a similar pattern depicting that the baseband channel has suffered crosstalk from another signal, which in this case the crosstalk is from the data of the subcarrier channel. On the other hand, the subcarrier channel eye is more noise dominated.

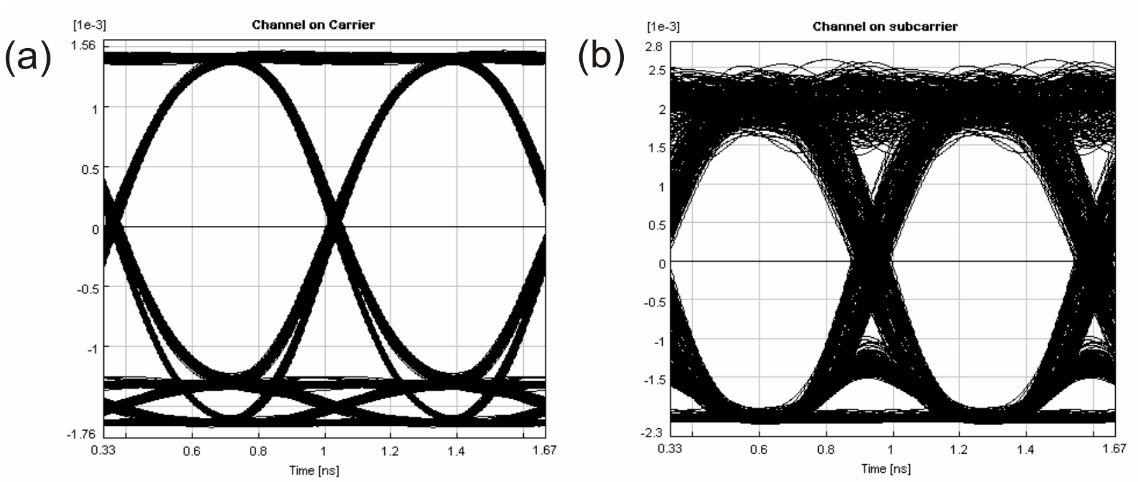

Fig. 3.8: Eye pattern for (a) baseband channel and (b) subcarrier channel, where both data streams are synchronised.

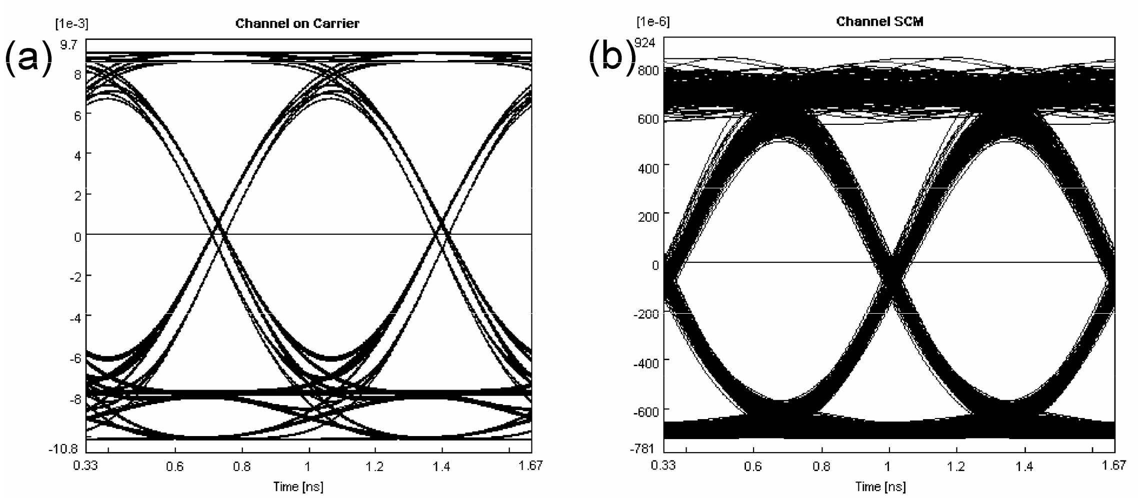

Fig. 3.9: Eye pattern for (a) baseband channel and (b) subcarrier channel, where both data streams are independent.

3.3.5. CSR analysis

Before the theoretical analysis of the subcarrier modulation characteristic in the next section, this sub-section discusses one of the solutions to lessen the negative impact from the crosstalk on the BER performance of the baseband channel by reducing the RF input power for the subcarrier signal. However, lower RF input power may result in a worse BER performance for the subcarrier channel. Here, the evaluation on the impact of different RF input power for subcarrier signal is carried out to investigate the performance trade-off between subcarrier and baseband channels.

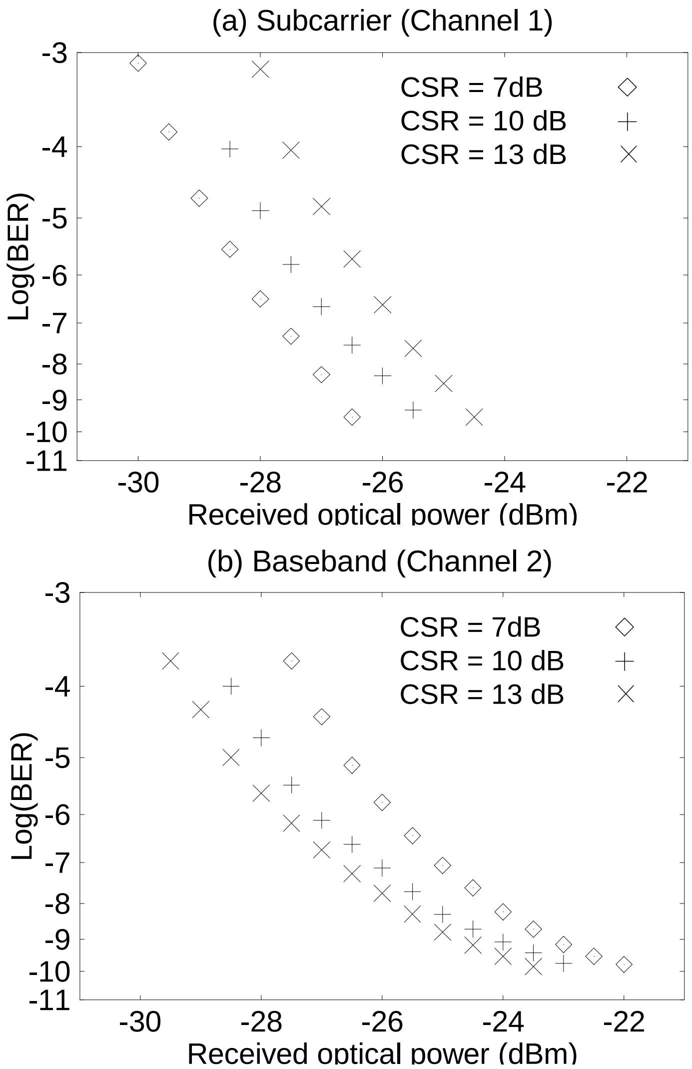

Fig. 3.10. BER measurements that corresponding to the different CSR where (a) and (b) show the BER measurement for subcarrier and baseband channels with three different CSRs (CSR = 7dB, 10dB, and 13dB) at 1555.16 nm.

The same experiment as shown in Fig. 3.1 is repeated with the RF input power of the subcarrier signal is changed from 11 dBm to 8 dBm and to 5 dBm into the mixer, while keeping the baseband amplitudes constant (which changes the CSR of the optical signal from 7 dB to 10 dB and 13 dB) to observe the signals performance trade-off. When the RF signal amplitude is decreased, the CSR will increase and change the receiver sensitivities for both channels. Fig. 3.10 (a) and (b) show the BER curves of the two channels corresponding to different CSR. It is noted that the baseband channel tends to have better BER performance when the power ratio increases from 7 dB to 10 dB and to 13 dB. This is due to the reduction of the optical crosstalk from the subcarrier channel into the baseband channel after filtering. However, the trade-off will be a worse BER performance for the subcarrier channel due to the reduction in the modulation depth of the subcarrier signal with the decrease in the subcarrier power and the increase in residual power from the other channel due to non-ideal optical filtering by the DI. However, it is noted that in all cases the receiver sensitivity at BER of 10^{-9} is within acceptable limits.

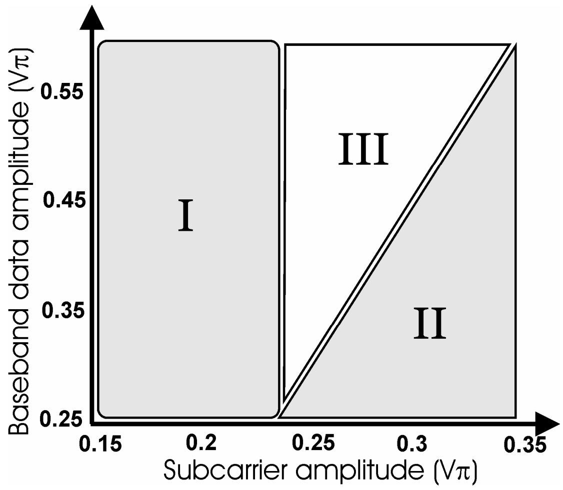

Figure 3.11. The three bias regions (approximate only) identified for the proposed scheme.

In order to verify the above statements and the change of BER curves' properties in Fig. 3.10, detailed simulations were carried out by changing the drive amplitudes of the two signals within reasonable limits into the modulator, and the bias regions for good BER performance for both channels were identified. A summary of the results that shows three distinct drive amplitude regions identified in biasing the MZM (note the depicted regions are approximately only as there can be minor deviations with different component responses) is shown in Fig. 3.11. Region I is limited by the received power on the subcarrier channel due to low subcarrier modulation. Region II is non ideal due to the error floor in the baseband channel caused by high amplitude of the subcarrier signal. Region III is the optimum bias region with good transmission performance for both channels.

An additional advantage of this technique is the fixed channel separation of the two data streams instead of using two independent wavelength sources, which can drift apart with respect to each other. Furthermore, the channel bandwidth can be readily increased by larger subcarrier frequency and smaller differential delay for the DI such as a 50 ps differential delay with the subcarrier frequency at 10 GHz. This will also ease the wavelength stability requirements. In this case, the wavelength deviation, which maintains the BER sensitivity (power measured before the DI) within a 3 dB margin, was identified to be 11.4 GHz for the baseband channel and 1.7 GHz for the subcarrier channel. A mentioned before, the subcarrier channel is more sensitive to wavelength misalignment due to its relatively lower power.

3.4. Characteristics of Subcarrier Multiplexing Technique

From the previous section, it is clearly shown that by reducing the subcarrier RF input power to increase the CSR value, the baseband channel (data channel modulated on the optical carrier) will result a better BER performance. This is due to the reasons that if the total signal is detected, then as expected spectral components other than the one modulated on the subcarrier signal do not appear in the RF signal (ignoring higher order nonlinear terms). However, when the optical signal is filtered, the baseband components do appear as shown in the RF spectral diagrams in [19]. This phenomenon has been recently discussed in [20].

At the OLT transmitter end as presented in Fig. 3.1, the output optical field of the modulator is given by [22]

$$E(t) = E_{in}\exp(j\omega_c t)\times\left\{\cos\left[\frac{\pi}{V_\pi}\left(V_m(t)\cos(\omega_{rf}t)+V_b\right)\right]\right\}, \tag{3.1}$$

where V_b is the MZM bias voltage, E_{in} and ω_c are the amplitude and carrier frequency of the input carrier respectively; $\omega_{rf} = 2\times\pi\times f_{rf}$ is the angular frequency of the LO for subcarrier channel and V_π is the driving voltage of the modulator for π shift. The $V_m(t)$ represents the baseband data voltage, which can be expressed as [20]

$$V_m(t) = \sum_{k=1}^{\infty} b_k A_m f_k(t), \qquad kT_b \le t \le (k+1)T_b, \tag{3.2}$$

where T_b represents the bit duration of the downstream data and b_k is the bit value in 0 or 1; A_m is the amplitude and $f_k(t)$ is the data waveform. Expanding equation (3.1) in terms of Bessel functions will lead to the following expression [20]

$$\begin{aligned} E(t) = E_{in}\exp(j\omega_c t)\Bigg\{&\cos\left(\pi\frac{V_b}{V_\pi}\right)\left[J_0(x(t)) + 2\sum_{n=0}^{\infty}(-1)^n J_{2n}(x(t))\cos(2n\omega_{rf}t)\right] \\ &-2\sin\left(\pi\frac{V_b}{V_\pi}\right)\sum_{n=0}^{\infty}(-1)^n J_{2n+1}(x(t))\cos((2n+1)\omega_{rf}t)\Bigg\}, \end{aligned} \tag{3.3}$$

where $x(t) = \pi V_m(t)/V_\pi$. From (3.3), ω_c, $\omega\pm\omega_{rf}$, $\omega\pm 2\omega_{rf}$, … represent the frequency components contained in the subcarrier modulated optical field, where ω_c is the optical carrier and the other terms are the subcarriers.

After envelope detection of the signal in equation (3.3), the electrical power obtained is

$$P(t) = |E(t)|^2 = \frac{|E_{in}|^2}{2}\left\{ J_0^2(x(t)) + 2\sum_{k=1}^{\infty} J_i^2(x(t)) + \sum_{k=0}^{\infty} J_k J_{k+1}(x(t))\cos(\omega_{rf} t) + \ldots \right\}. \quad (3.4)$$

Using the Neumann's addition theorem of Bessel function [20], the baseband component of the signal obtained is constant and with no data spectrum component,

$$P_{Base}(t) = \frac{|E_{in}|^2}{2}\left[J_0^2(x(t)) + 2\sum_{k=1}^{\infty} J_k^2(x(t)) \right] = \frac{|E_{in}|^2}{2}. \quad (3.5)$$

However, if optical filter is used to separate the carrier (baseband channel) and subcarrier (subcarrier channel), their corresponding power $P_{carrier}$ and $P_{subcarrier}$ respectively, as

$$P_{carrier}(t) = |E_{in}|^2 \frac{J_0^2(x(t))}{2}, \quad (3.6)$$

$$P_{subcarrier}(t) = |E_{in}|^2 \sum_{k=1}^{\infty} J_k^2(x(t)) = \frac{|E_{in}|^2}{2} - P_{carrier}(t). \quad (3.7)$$

Equation (3.6) shows that the power of optical carrier is a function of modulation signal voltage $V_m(t)$. Considering small signal modulation and the characteristic of zero-order Bessel function, $P_{carrier}$ decreases with the increase of $x(t)$ [20]. As a result, the carrier signal (baseband channel) after optical separation represents an inverted version of the modulated data in subcarrier channel, which results in subcarrier channel crosstalk to data channel modulated in the optical carrier. This analysis has verified the subcarrier channel crosstalk effect on BER performance demonstrated in section 3.3.

3.5. Conclusion

The chapter discussed one of the challenges in WDM-PON technology - independent services provisioning. A simple scheme to generate and separate two independent high bandwidth baseband channels using a single laser and modulator was proposed in this chapter. The scheme transmits one channel at baseband and the other at a low frequency subcarrier with data modulated in ASK format. The received signal is optically separated using a delay interferometer that allows both channels to be detected independently using standard baseband receivers. A multi channel experimental demonstration of the scheme was presented.

Section 3.3 described the crosstalk effect on baseband channel from subcarrier signal, which is one of the main challenges of the proposed scheme. Therefore, a solution for this has been presented where the RF signal amplitude of the subcarrier channel is varied to obtain a balanced result for both channels. Also, different drive amplitude regions in biasing the MZM was identified by detailed simulation to determine the optimum bias region with good transmission performance for both baseband and subcarrier channels. The experimental and simulation results confirm the feasibility of the technique at data rates of 1.5 Gb/s for multiple wavelength channels before and after 20 km of fibre transmission. The characteristic of subcarrier multiplexing technique was also discussed in section 3.4 to analyse the subcarrier crosstalk to baseband channel.

The proposed scheme can be applied in a WDM-PON, where two independent services can be efficiently transmitted over an existing network with relatively minor changes to ONUs at the customer premises with multiple advantages for the service providers.

3.6. References

[1] L. G. Kazovsky, W.-T. Shaw, D. Gutierrez, N. Cheng and S.-W. Wong, "Next-generation optical access networks," *J. Lightwave Tech.*, vol. 25, no. 11, pp. 3428-3442, Nov. 2007.

[2] G.-K. Chang, A. Chowdhury, Z. Jia, H.-C. Chien, M.-F. Huang, J. Yu, G. Ellinas, "Key Technologies of WDM-PON for Future Converged Optical Broadband Access Networks," *IEEE/OSA J. Opt. Commun. and Networking*, vol 1, no. 4, pp. C35-C50, Sep. 2009.

[3] C.-H. Lee, W. V. Sorin, B. Y. Kim, "Fiber to the Home Using a PON Infrastructure," *J. Lightwave. Tech.*, vol. 24, no. 12, pp. 4568-4583, Dec. 2006.

[4] U. Hiblk, T. Saniter, F.-J. Westphal, "High capacity WDM overlay on a passive optical network," *IEE Electron. Lett.*, vol. 32, no. 23, pp. 2162-2163, Nov. 1996.

[5] P. P. Iannone, K. C. Reichmann, N. J. Frigo, "High-speed point-to-point and multiple broadcast services delivered over a WDM passive optical network," *IEEE Photon. Tech. Lett.*, vol. 10, no. 9, pp. 1328-1330, Sep. 1998.

[6] E. S. Son, K. H. Han, J. K. Kim, Y. C. Chung, "Bidirectional WDM passive optical network for simultaneous transmission of data and digital broadcast video service," *J. Lightwave. Tech.*, vol. 21, no. 8, pp. 1723-1727, Aug. 2003.

[7] Y. C. Chung, "Challenges Toward Practical WDM PON," in *Proc. Optoelectronics and Communication Conference*, paper 6C4-1, 2006.

[8] J. Marti, J. Capmany, "Modeling optically prefiltered AM subcarrier multiplexed systems," *IEEE Transac. Microwave Theory and Techniques*, vol. 43, no. 9, pp. 2249-2256, Sep. 1995.

[9] J. Marti, J. Capmany, H. Mangharam, "Crosstalk analysis in optically prefiltered subcarrier multiplexed systems," *IEE Electron. Lett.*, vol. 29, no. 23, pp. 2054-2055, Nov. 1993.

[10] Z. Zhu, V. J. Hernandez, M. Y. Jeon, J. Cao, Z. Pan, and S. J. B. Yoo, "RF photonics signal processing in subcarrier multiplexed optical-label switching communications systems," *J. Lightwave. Tech.*, vol. 21, no. 12, pp. 3155-3166, Dec. 2003.

[11] M. Y. Jeon, Z. Pan, J. Cao, S. J. B. Yoo, :BER performance of all-optical subcarrier label swapping with 2R regeneration," *IEEE Photon. Tech. Lett.*, vol. 16, no. 1, pp. 323-325, Jan. 2004.

[12] J. Yang, M. Y. Jeon, J. Cao, Z. Pan, S. J. B. Yoo, "Performance monitoring in transparent optical networks using self-monitoring optical-labels," *IEE Electron. Lett.*, vol. 40, no. 21, pp. 1370-1372, Oct. 2004.

[13] M. Y. Jeon, Z. Pan, J. Cao, Y. Bansal, J. Taylor, Z. Wang, V. Akella, K. Okamoto, S. Kamei, J. Pan, S. J. B. Yoo, "Demonstration of all-optical packet switching routers with optical label swapping and 2R regeneration for scalable optical label switching network applications," *J. Lightwave. Tech.*, vol. 21, no. 11, pp. 2723-2733, Nov. 2003.

[14] P. D. Sargis, R. E. Haigh, K. G. McCammon, S. Young, "Subcarrier multiplexing with dispersion reduction," *IEE Electron. Lett.*, vol 31, no. 20, pp. 1769-1770, 1995.

[15] P. D. Sargis, B. D. Henderer, M. E. Lowry, “10-Gb/s subcarrier multiplexed transmission over 490 km of ordinary single-mode fiber without dispersion compensation,” *IEEE Photon. Tech. Lett.*, vol 9, no 12, pp. 1658-1660, Dec. 1997.

[16] J. Yu, G-K. Chang, A. Chowdhury, “Detecting Burst-Mode Optical Label or Payload Generated by OCSS Technique Using Conventional Receivers,” *IEEE Photon. Tech. Lett.*, vol. 17, no. 7, pp. 1567-1569, 2005.

[17] A. Chowdhury, J. Yu, G.-K. Chang, “All-optical label swapping for same wavelength data switching using optical carrier suppression, separation and without regular wavelength converter,” *IEEE Photon. Tech. Lett.*, vol. 17, no. 5, May 2005.

[18] J. Yu, G-K. Chang, “A Novel Technique for Optical Label and Payload Generation and Multiplexing Using Optical Carrier Suppression and Separation,” *IEEE Photon. Tech. Lett.*, vol 16, no. 1, pp. 320-322, Jan. 2004.

[19] M. Attygalle, T. Anderson, D. Hewitt, A. Nirmalathas, “WDM Passive Optical Network with Subcarrier Transmission and Baseband Detection Scheme for Laser Free optical Network Units,” *IEEE Photon. Tech. Lett.*, vol. 18, no. 11, pp. 1279-1281, 2006.

[20] Z. Xu, Y. J. Wen, W.-D. Zhong, T. H. Cheng, M. Attygalle, X. Cheng, Y.-K. Yeo, Y. Wang, C. Lu, “Characteristics of Subcarrier Modulation and Its Application in WDM-PONs,” *J. Lightwave Tech.*, vol. 27, no. 12, pp. 2069-2076, Jun 2009.

[21] G. Foster, “Anatomy of an Eye Diagram – a Primer,” Synthesys Research Inc white papers, pp. 1-8, 2004.

[22] G. H. Smith, D. Novak, Z. Ahmed, “Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators,” *IEEE Trans. Microw. Tech.*, vol. 45, no. 8, pp. 1410-1415, Aug. 1997.

4 EPON Incorporating Active Remote Repeater Node with Layer 2 Forwarding

4.1. Introduction

The IEEE 802.3ah Ethernet passive optical network (EPON) and ITU-T G.984 Gigabit passive optical network (GPON) standards have been discussed in Chapter 2 as the most popular time-division multiplexing (TDM) PON technologies in the world. Some of the key differences between both standards are: 1) EPON provides symmetrical 1 Gb/s transmission capacity while GPON is capable of supporting up to asymmetrical 2.5 Gb/s downstream and 1.2 Gb/s upstream transmission capacity [1]; 2) EPON standard defines that each OLT is capable of supporting 32 ONUs while GPON standard defines a minimum split-ratio of 1:32 with 1:64 and 1:128 are both achievable theoretically [1]; and 3) EPON uses Ethernet frames to transport IP packets while GPON uses Gigabit encapsulation methods (GEM), which is capable of carrying Ethernet, asynchronous transfer mode (ATM) and voice traffic [1]. Despite the differences between two standards, EPON has been selected as the main technology for the work discussed in the rest of the thesis, though the concepts can be equally applied for GPON.

The basic Ethernet passive optical network (EPON) architecture as discussed in Chapter 2 is shown in Fig. 4.1. The downstream transmission frames that are sent by the optical line terminal (OLT) to every optical network unit (ONU) are in broadcast format. Every ONU filters the frames that are not destined to it based on the given physical logical link identity (LLID) assigned by the OLT. However in the upstream transmission, time division multiple access (TDMA) scheme is used where each ONU has a certain transmission period allocated by the OLT to avoid collision at the passive combiner and effectively share the channel capacity between all ONUs.

Despite the advantages of EPON in high efficiency on carrying variable size Internet Protocol (IP) packets, broad market potential and economical Ethernet products; research issues on EPON’s efficiency and scalability draw a lot of interests from researchers. Dynamic bandwidth assignment (DBA) techniques have been proposed to improve the network efficiency through channel bandwidth assignment [2-6]. Furthermore, providing service level agreements (SLAs) and enforcing traffic shaping and policing for each individual user is yet another important research topic [7-9]. Thus, researchers have proposed advanced EPON architectures with guaranteed performance parameters such as packet latency, loss and bandwidth [10]. These proposals equip EPON with the ability to better allocate bandwidth or channel capacity for improving quality of service (QoS). However, controlling the flow of the traffic is an important issue in EPON. The IEEE 802.3ah standard defines that EPON will be using only the point-to-point (PTP) emulation and an auxiliary single-copy broadcast (SCB) port at the OLT [7]. In such a configuration, an EPON with N ONUs will result the OLT to contain N+1 medium access control (MAC) ports; where one for each ONU with PTP emulation (for both upstream and downstream transmissions) and one for broadcasting to all ONUs (only for upstream transmission) [7]. This configuration causes the local traffic or communications between ONUs to be transmitted through the network upstream and then downstream (from ONU to OLT and then OLT to ONU). As a consequence, local traffic redirection at the OLT uses up the channel capacity and increase latency due to buffering and traffic rescheduling at the OLT. Furthermore, the incoming external Internet traffic will also be buffered at the OLT to cause further increase the traffic delay.

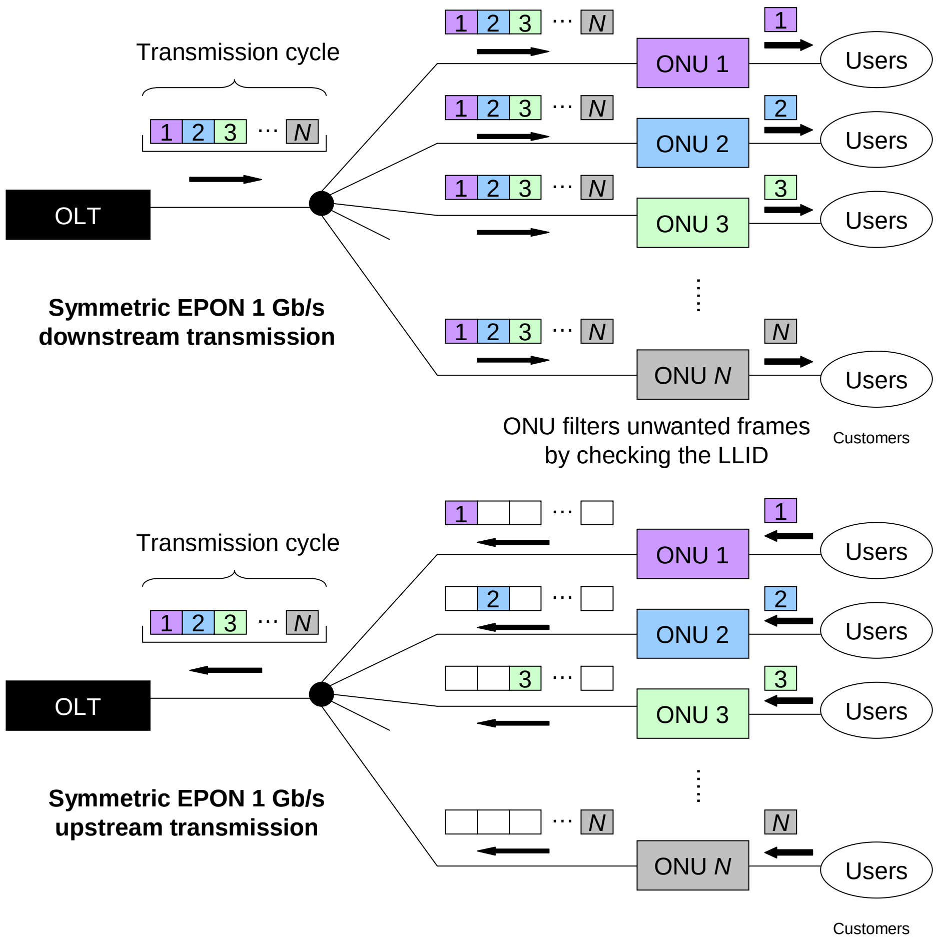

Fig. 4.1: EPON architecture demonstrating downstream and upstream transmissions.

In order to address these issues, researchers proposed the use of active devices such as Ethernet switch in the network [11-15]. The use of Ethernet switch in the access optical network enables a dedicated medium in which each end user is allowed independent access. Each customer has a home gateway directly connected to the Ethernet router in the central office (CO) or street cabinet by a direct fibre [14]. Although active Ethernet has the advantages of extending the transmission distance, providing larger bandwidth per user and controlling network flow, it makes optical access networks a costly switched network and makes cost effective EPON redundant. As a result, we proposed a simple hybrid or intermediate solution to EPON with a simple active remote repeater node (RN) with Open System Interconnection (OSI) reference model's layer two forwarding scheme without modifying any functionality of the EPON protocol [16]. This scheme increases the network capacity utilisation and improves the network's packet transmission by reducing the frame transmission delay. This proposed architecture also creates the potential to increase the number of subscribers or capacity per user, and also the network coverage due to regeneration.

This chapter is organised as follows. Section 4.2 discusses the logical topology emulation (LTE) of IEEE 802.3ah 1G-EPON standard and its limitation. Section 4.3 presents the proposal of the active RN with layer two forwarding scheme to improve traffic control in EPON system. In this section, the multi-point control protocol (MPCP) auto-discovery function will be discussed in detail and how the active RN gathers information in populating forwarding tables will be explained. Section 4.4 discusses the simulation set-up of the EPON incorporating active RN with layer two forwarding scheme. In section 4.5, simulation and theoretical analysis results to prove the advantages of the proposed scheme in terms of downstream internet traffic and local traffic delays will be presented. Finally, section 4.6 summarises the overall chapter.

4.2. Local Traffic in IEEE 802.3ah LTE

The IEEE 802.3ah standard has defined the LTE function to comply with the IEEE 802 architecture as discussed in Chapter 2. This requires the OLT to contain *N*+1 MAC ports, where *N* MAC ports are for PTP emulation for each *N* ONU while one for broadcasting to all ONUs (single-copy broadcast channel) as shown in Fig. 4.2. The SCB channel is to be used for downstream broadcast only [7]. Therefore, only PTP emulation will be used for all upstream transmission; which also means that all upstream frames are required to be forwarded to the OLT Bridge. The bridging function in the OLT will decide to either forward the received frame from an ONU downstream back to the PON (inter-ONU communication) or forward it to the network layer to determine it's IP destination and then pass on to the appropriate port for transmission.

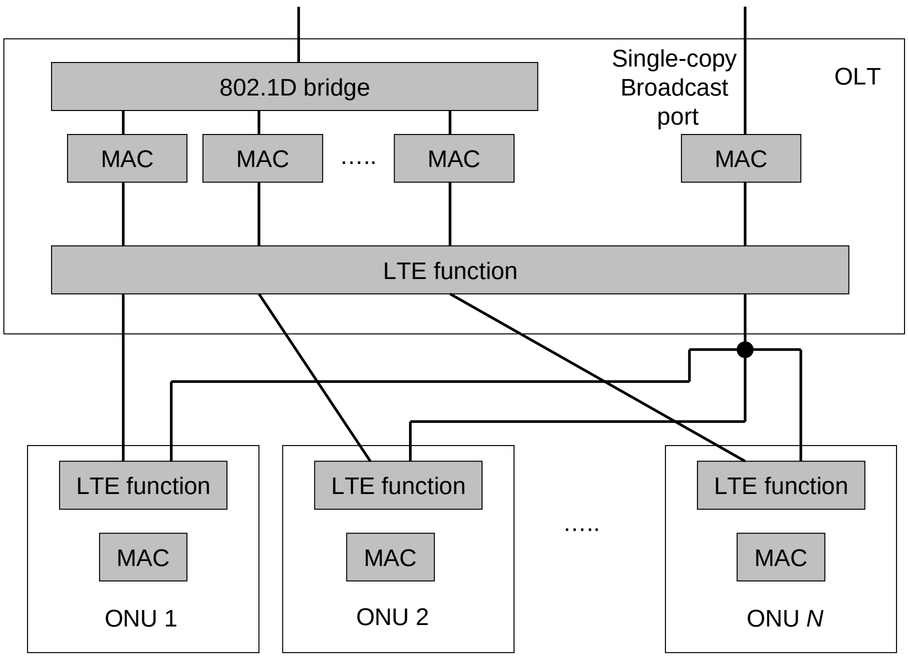

Fig. 4.2: Combination of point-to-point (PTP) and shared-medium emulation (SME) mode for IEEE 802.3ah [7].

Due to the use of PTP emulation function in current 1G-EPON standard, inter-ONUs communications are required to be routed through OLT's bridge/switch as shown in Fig. 4.3, which describes an example of inter-ONU communication showing the travel path of traffic originating from ONU 1 with the destination of ONU 2. This frame will be inserted with

ONU 1's LLID and ONU 2's MAC address in order to get accepted by the OLT LTE function. Hence, the LLID tag will be removed and pass on to the OLT bridge. The bridge decides the destination of the frame and forwards the frame with modified LLID tag (ONU 2's LLID) to the PON interface. Although the LTE function in EPON standard is compliant with IEEE 802 architecture and enable logical broadcast domain within the PON, it also decreases the effective downstream bandwidth (local traffic will be inserted into downstream transmission, which reduces the available bandwidth available for external traffic) and increases the latency for local traffic, since the traffic has to be rescheduled and buffered at the OLT together with external traffic (from Internet).

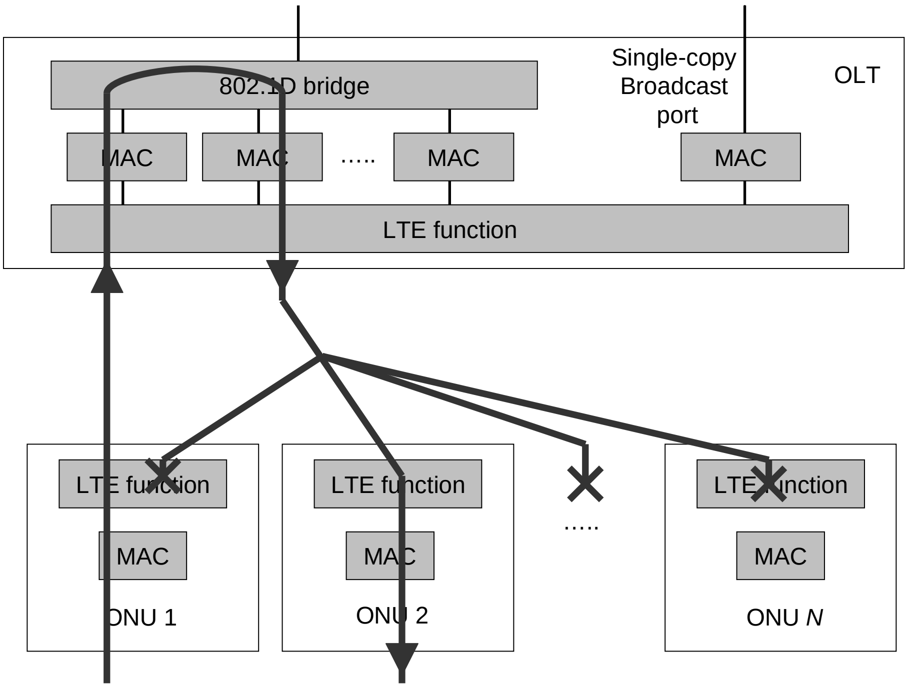

Fig. 4.3: Inter-ONU communication path through OLT bridging and PTP emulation.

Round trip time (RTT) measurement of EPON has been studied in Chapter 2. The RTT measurement includes the downstream transmission time, upstream transmission time and a specific wait time in the ONU. Using the RTT measurement, the delay of an inter-ONU frame can be determined as shown in Fig. 4.4. Following the receive of GATE message from the OLT that assigns a specific upstream transmission timeslot for ONU 1, the frame suffers a T_{wait_ONU}, which indicates the waiting time for upstream transmission. However, note that the frame might not be accepted for transmission in very high traffic load and will suffer another round-trip delay. Subsequently, this frame will suffer an upstream propagation delay ($T_{upstream}$)

to reach the OLT. As soon as the frame is received by the OLT, it will be sent to the OLT bridge/switch to determine the next destination. Hence, the frame will be stored in the downstream buffer pending for transmission. The whole process in the OLT denotes the T_{wait_OLT} as shown in Fig.4.4. This delay is directly related to the processing speed of the OLT, OLT buffer size and traffic load. If successfully transmitted downstream, the frame will experience a downstream propagation delay, $T_{downstream}$ upon arriving at ONU 2. Therefore, the total delay that will be experienced by the frame transmitted by ONU 1 and arrive at ONU 2 is given by:

Total_delay: $T_{wait\_ONU} + T_{upstream} + T_{wait\_OLT} + T_{downstream}$.

Note that this calculation does not include the buffer delay in the ONU and frame re-transmission delay due to limited ONU buffer size and frame loss, which will become significantly high at high traffic load.

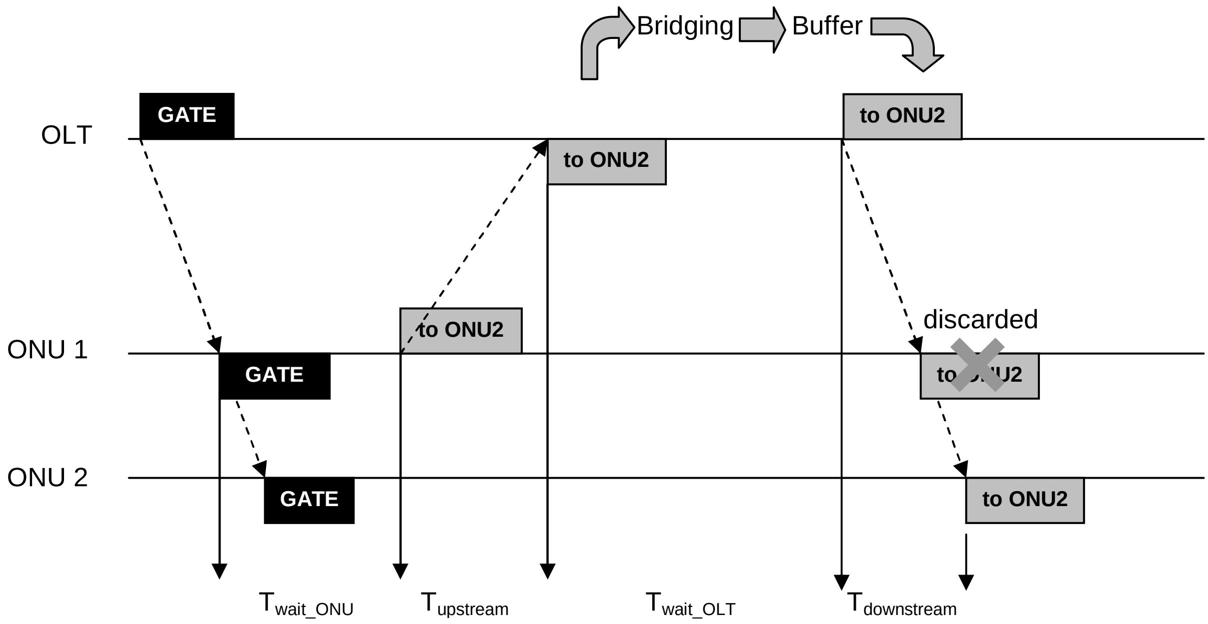

Fig. 4.4: RTT for an inter-ONU frame.

4.3. EPON Incorporating Active RN with Layer Two Forwarding Scheme

In this section, the proposal of an active RN with layer two forwarding scheme will be presented. This proposed scheme enables the local traffic between ONUs to be redirected at the active RN. This traffic redirection aims to reduce the delay for local traffic between ONUs and also the delay for external downstream traffic due to the absence of local traffic at the OLT to contend with the limited downstream buffer.

4.3.1. Background overview on repeater based PON

National Information and Communication Technology Australia (NICTA) optical access research group has proposed and have patented a simple regenerator based active node in PON in order to increase the feeder length of a PON and increase the number of users in the network [17-20]. Fig. 4.5 (a) shows the architecture of a fibre-to-the-home (FTTH) system using upstream regenerated remote repeater, where conventional 1×N star coupler (SC) is replaced by a 2×N SC [17, 19]. One arm of the SC on OLT is connected to the remote repeater and the other arm of the SC to transmit downstream signals through the SC and bypass the remote repeater. An isolator is used at the downstream path to prevent upstream signals from entering. The downstream and upstream signals are then separated or combined using a coarse wavelength division multiplexer (CWDM) [15]. The upstream signals can be 2R (re-amplification, reshaping) or 3R (re-amplification, reshaping, retiming) regenerated at the remote repeater using a burst-mode receiver (BMR), a burst-mode transmitter (BMT) and a clock data recovery (CDR) module [17]. The use of an upstream repeater provides the opportunity for much lower cost implementation of ONU using low power and low cost optical transmitters such as vertical cavity surface emitting laser (VCSEL) based transmitters [17]. This architecture enables the upstream signal to be regenerated without modifying the internal frame structure [19].

However, PON transmitter and receiver are usually commercially available as a single bidirectional transceiver (TRX) unit. This enables the bidirectional regeneration of traffic at the RN as shown in Fig. 5.5 (b) [19]. This architecture will allow an extension in feeder fibre length and split-ratio. By using standard EPON OLT and ONU transceivers, the feeder fibre reach can be increased from 20 km to approximately 60 km and split-ratio from 1:32 to 1:256 [19]. This increase in reach and split-ratio provides an upgradeability solution for existing PON deployment using low cost components [19]. However, as the number of users increase, the bandwidth per user decreases since the PON link capacity is shared among all ONUs. If local traffic can be kept localised without redirecting at the OLT, a large portion of downstream bandwidth (used for local traffic) can be saved and hence increase the average bandwidth per user.

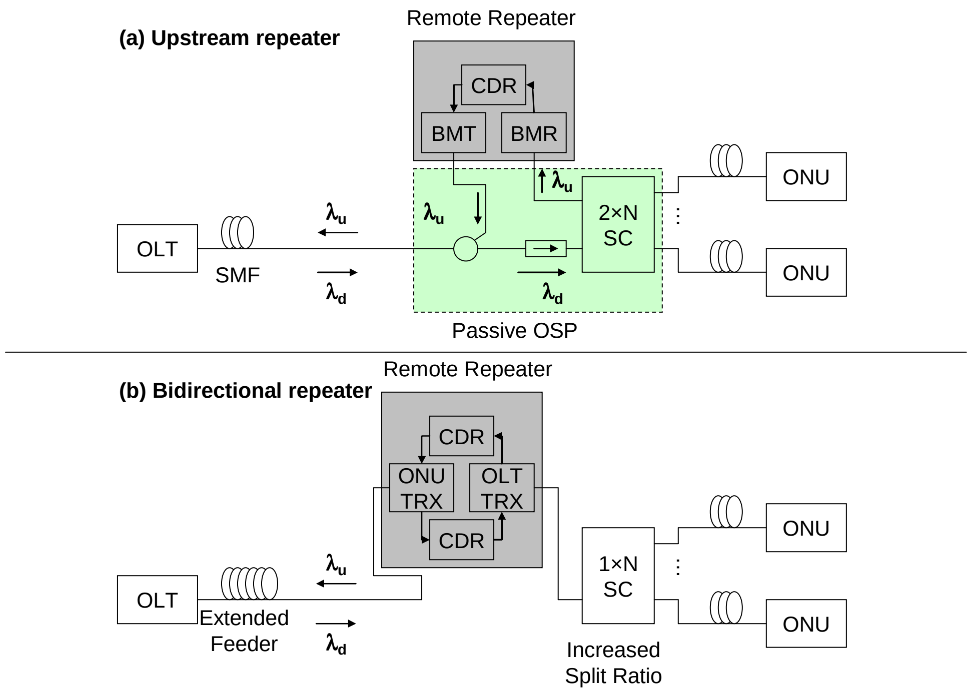

Fig. 4.5: Remote repeater designs for FTTH system with a) shows the upstream only repeater and b) shows the bidirectional repeater [19].

Since the repeater node is acting as an active node in EPON, a simple layer two forwarding technique can be used at the active RN to better utilise the EPON bandwidth both in upstream and downstream directions. This technique allows frames to be forwarded to appropriate customer units or ONUs, and frames that are not destined to the ONUs beyond the active RN will be filtered. However, any technique or proposed scheme that is designed incorporating EPON has to comply with the overall IEEE 802 standard. Therefore, this proposed architecture that is presented here should not affect the current MPCP but work in conjunction with the protocol. It will also cause no impact on the DBA that is implemented on top of EPON. Furthermore, the details of this technique will be built under the conditions of no changes will be applied to the OLT and the ONU structures, which means that the regenerator RN will act as an additional unit to the networks; without the active RN, the PON will work as a basic PON.

4.3.2. MPCP auto-discovery mode

MPCP is critical in the EPON incorporating active RN with layer two forwarding scheme architecture. The information transferred in MPCP between the OLT and ONUs assists the active RN to learn and construct the layer two forwarding table as described later in the next section. As discussed in Chapter 2, an ONU can only commence transmission if it is granted a timeslot from the OLT. However, if the OLT does not know the present state of a particular ONU, it will not send the grant message (GATE) to the ONU. Therefore, auto-discovery mode is used to register newly joined ONUs. In this mode, four MPCP messages are used: discovery GATE, REGISTER_REQ, REGISTER, and REGISTER_ACK [21, 22]. These four messages are carried in MPCP control frames (Fig. 4.6).

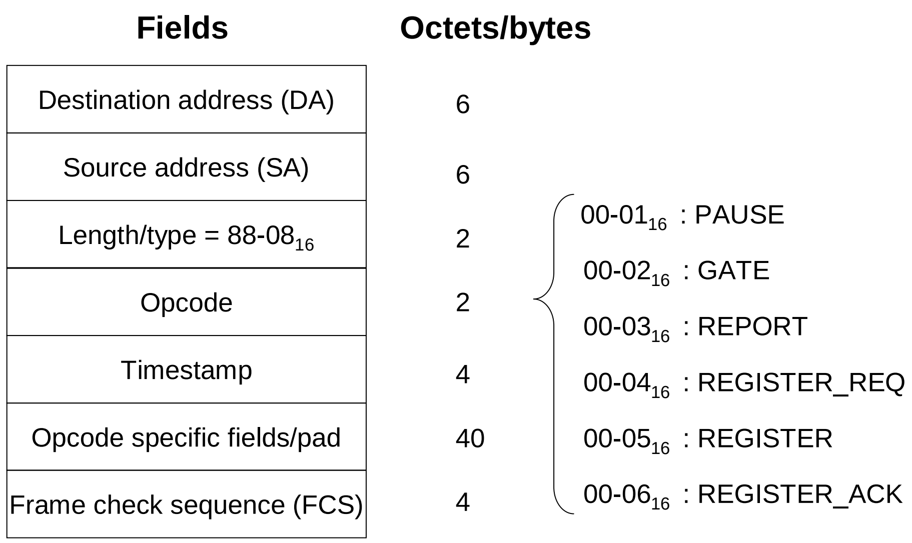

Fig. 4.6: EPON MPCP frame.

The auto-discovery mode [7, 21, 22] consists of four major steps as shown in Fig. 4.7:

Step 1:

The OLT decides to initiate a discovery round and allocates a discovery window, which is an interval of time when no previously initialised ONUs are allowed to respond and transmit register request messages. The DBA agent in the OLT is responsible to ensure that no active ONUs are scheduled to transmit during the discovery window. To commence the discovery process, the OLT sends a discovery GATE message to advertise the start time of the discovery slot and its length.

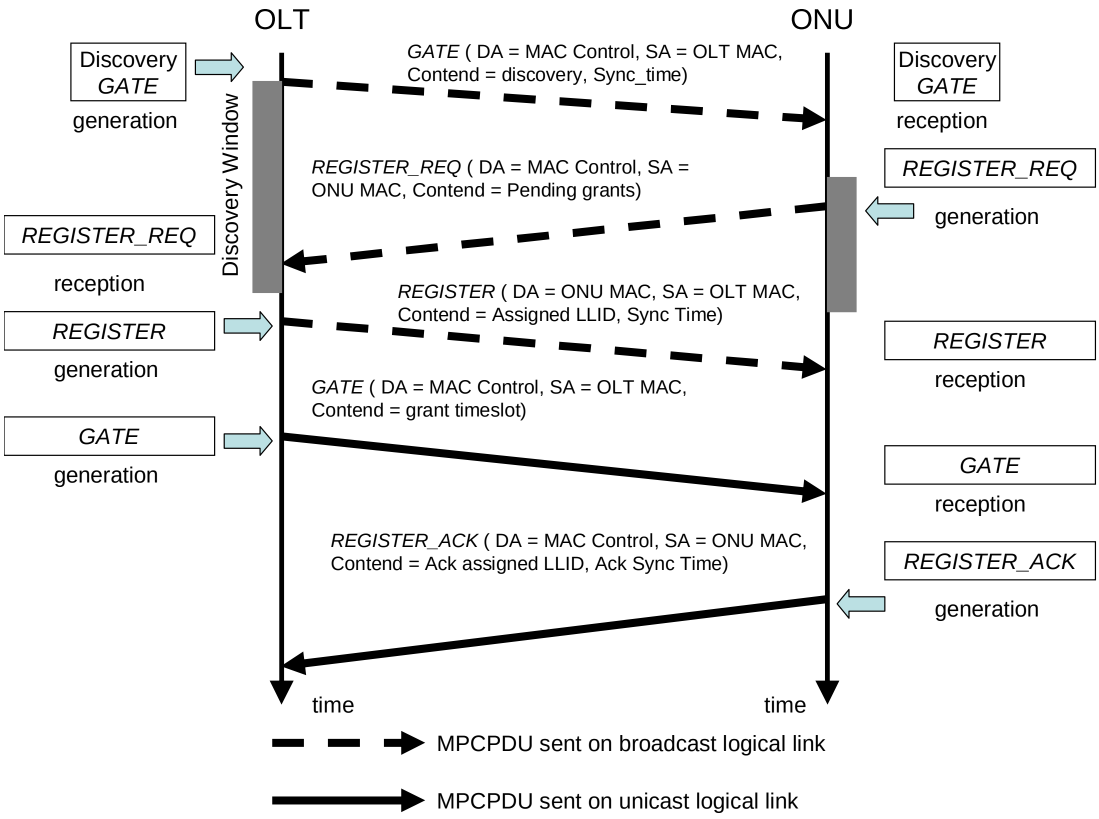

Figure 4.7: EPON MPCP auto-discovery process

Step 2:

All ONUs will receive the discovery GATE message but only the un-initialised ONUs will respond to the discovery GATE message. Upon receiving the discovery GATE message, an ONU will set its local time to the timestamp from the discovery GATE message that it receives. When the local clock at the ONU reaches the start time of the discovery slot, the ONU will wait for an additional random delay and then transmit the REGISTER_REQ message. This random delay is aimed to avoid possible collisions if multiple un-initialised ONUs require to register. The REGISTER_REQ message contains the ONU's source address and a timestamp representing the ONU's local time. Upon receiving the REGISTER_REQ message at the OLT, the OLT calculates the ranging or RTT using the ONU's local timestamp.

Step 3:

After verification from the OLT on each ONU's REGISTER_REQ message, the OLT will issue the REGISTER message to an initialising ONU using the MAC address from previous REGISTER_REQ message. Furthermore, a physical LLID address that is unique for each ONU will be assigned by the OLT to the initializing ONU. Following the REGISTER message, the OLT will send a normal GATE (grant message) to the same ONU.

Step 4:

Finally, after receiving the REGISTER message and the normal GATE message, the ONU sends the REGISTER_ACK message to acknowledge and complete the discovery process in the timeslot granted by the previously received GATE message. The summary of the auto-discovery process is shown in Fig. 4.7.

4.3.3. EPON with active RN architecture

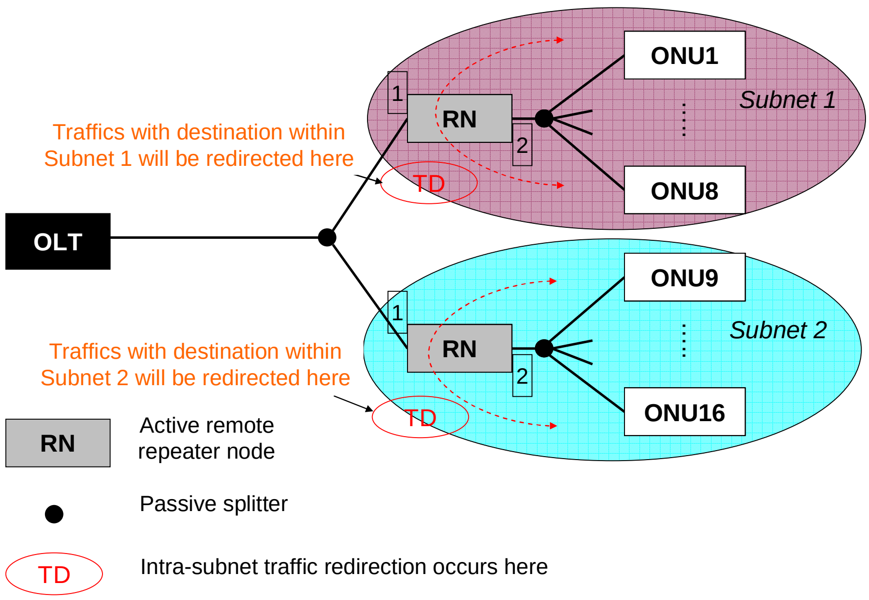

Fig. 4.8: EPON architecture incorporating active RN.

Common 'tree' architecture 1:2:16 will be used to evaluate the functions of the simple active RN as shown in Fig. 4.8. Normally, only one split point is used in an EPON system (1:16). Two splitting points are used for the proposed architecture is due to the reason that the active RN is required to filter downstream frames (with destination to ONUs that connect to other active RN) to create empty timeslot for accommodating redirected local intra-subnet traffic. If only one split point is used, which means that all ONUs are connected to the active RN; no frames can be filtered. Therefore, all ONUs in an EPON system is required to be allocated into at least two subnets. Furthermore, this proposed scheme assumes that each splitter node is located close to the customers and therefore burst-mode receiver is not required in the active RN. However, if a particular network design shows that each ONU will have different distances to the active RN, burst-mode receiver will be required. Nevertheless, the performance enhancement of using the active RN will not be affected.

A subnet can have an active RN before the passive splitter. As a consequence, the local traffic generated within the subnet is termed local intra-subnet traffic while the traffic generated from one subnet to another subnet is named local inter-subnet traffic. The active RN listens to all the incoming frames' header information and form the forwarding table to identify the MAC and LLID addresses of the ONUs in each subnet that allows the RN to filter and forward network traffic appropriately. The frame listening technique used in the active RN is similar to the Internet Group Management Protocol (IGMP) snooping technique used in a switch to obtain multicast information to snoop IGMP conversations between hosts and routers [23-25]. However, the frame listening technique used here has much simpler function to only read the layer two header of each frame to form the forwarding table.

The information received through listening to the EPON auto-discovery MPCP frames and normal EPON frames will be used to construct and maintain a forwarding table in the active RN. By listening to the discovery *GATE* message during the auto-discovery process, the MAC address of the OLT will be recorded. When an ONU is trying to register to the network by sending the *REGISTER_REQ* message, the MAC address of the ONU will be recorded in the forwarding table of the active RN. Following the completion of the auto-discovery process, the active RN will be able to record the LLID addresses from the ONUs that are connected to it through listening to the *REPORT* message or normal frames sent by the ONUs. With this information, a forwarding table below can be constructed.

PORT 1

MAC	LLID
OLT	OLT

PORT 2

MAC	LLID
ONU1	ONU1
ONU2	ONU2
ONU3	ONU3
ONU4	ONU4
ONU5	ONU5
ONU6	ONU6
ONU7	ONU7
ONU8	ONU8

Table 4.1: Remote Node 1 (refer to Fig. 4.8) forwarding table list.

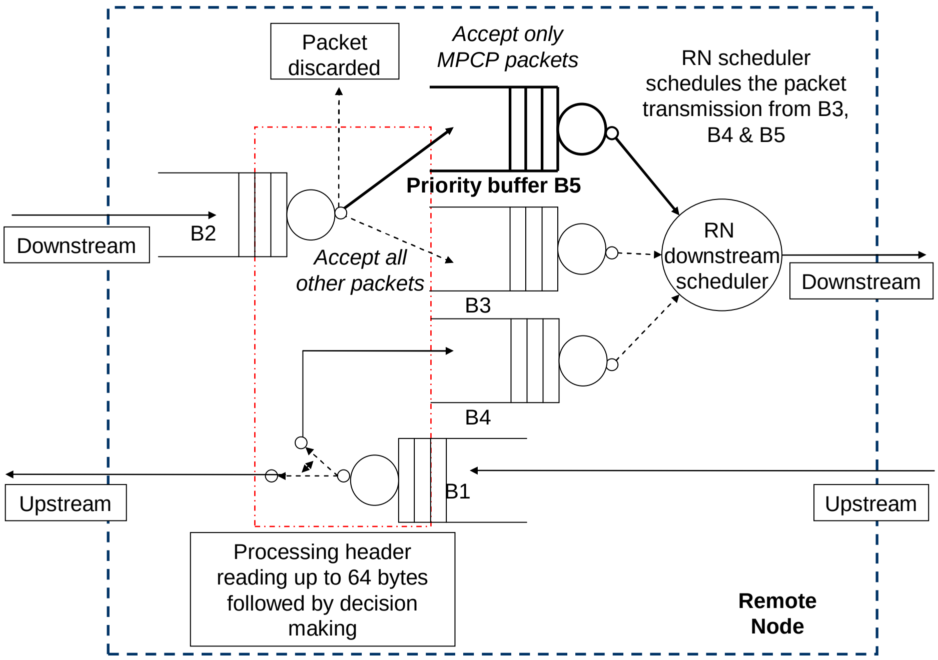

Fig. 4.9: Functional block diagram of an active RN.

Using the forwarding table, traffic generated by subnet 1 where the destinations are within subnet 1 (e.g. ONU1 to ONU4, ONU3 to ONU2) will be buffered or stored in the RN1 pending to be inserted into downstream free timeslots. At the downstream, frames which are not destined to ONU1 - ONU8 will be discarded and free timeslots will occur. These free timeslots will be used to transmit buffered or stored local intra-subnet frames. This creates an intra-subnet traffic redirection-point at the RN1 and the same process will occur at RN2 to create an intra-subnet traffic redirection-point for subnet 2 as shown in Fig. 4.8.

The functional block diagram of the active RN is shown in Fig. 4.9. When upstream frames are received at the active RN, the frame will be buffered at B1 as it takes a short period of time (t_1) to process the header reading up to 64 bytes (read destination MAC, LLID and source MAC addresses to determine the destination of the frame to be either redirected back to own subnet or transmitted upstream to the OLT). The header reading process is also crucial in updating the forwarding table regarding which ONU is connected to it. Other upstream frames that arrive within t_1 will also be buffered in B1. After the forwarding decision has been made to either redirect the frame back to the subnet or sending upstream to OLT, the particular frame will be either transmitted upstream (if the frame's destination is to OLT or Internet) or transmitted back downstream (if the downstream transmission is idle, otherwise the frame will be stored in the buffer B4). Similar header reading process occurs at frame processing in downstream direction except the decision will be either sending the particular frame downstream (MPCP frames will be inserted into priority buffer B5 and all other accepted frames will be stored in buffer B3) or discard the frame if the destination of the frame is not within the subnet connected to the active RN.

A downstream scheduler is needed in the active RN to schedule the downstream transmission. Packets in buffers B3 and B4 are transmitted downstream based on their arrival time. However, transmission priority will be given to buffer B5, which contains MPCP frames. The MPCP frames contain timing information in order to achieve synchronisation between the ONUs and OLT. This information is important for the ONUs to accurately transmit frames upstream in order to avoid collision at the passive combiner. Therefore the use of the RN scheduler and the assignment of constant wait time to MPCP frames are aimed at achieving negligible delay variability in the downstream path. Once a MPCP frame is accepted into buffer B5, the RN scheduler will make sure the frame suffers a wait time of 12.24 μs (equalling to the time to transmit the longest Ethernet frame of 1518 bytes in length plus inter-frame gap time in 1Gb/s link) and transmit it once the wait time is expired. This will lead to constant delay for MPCP packets and the ranging and synchronisation between the OLT and ONUs will not be affected. During the wait time, the RN scheduler will insert packets from buffers B3 and B4 based on arrival time. Since the total downstream bandwidth is shared equally among all ONUs, the frames' wait-time in the B3 and B4 will be negligible (micro-second range) as free timeslots will always occur due to packets destined to other subnets being dropped. Therefore, this will not have a significant effect on packet delay. On the other hand, buffer B2 is used to store the incoming downstream frames during the header reading and processing. The summary of the frame processing technique in the active RN is shown in Fig. 4.10. Note that the active RN needs to read only the first 64 bytes of the frame header (similar to Fragment-free switching technique [26-28]) to determine the source and destination addresses. Therefore a fixed processing delay will be assumed in the proposed architecture for both downstream and upstream pass-through traffic; hence the ranging in EPON will not be affected.

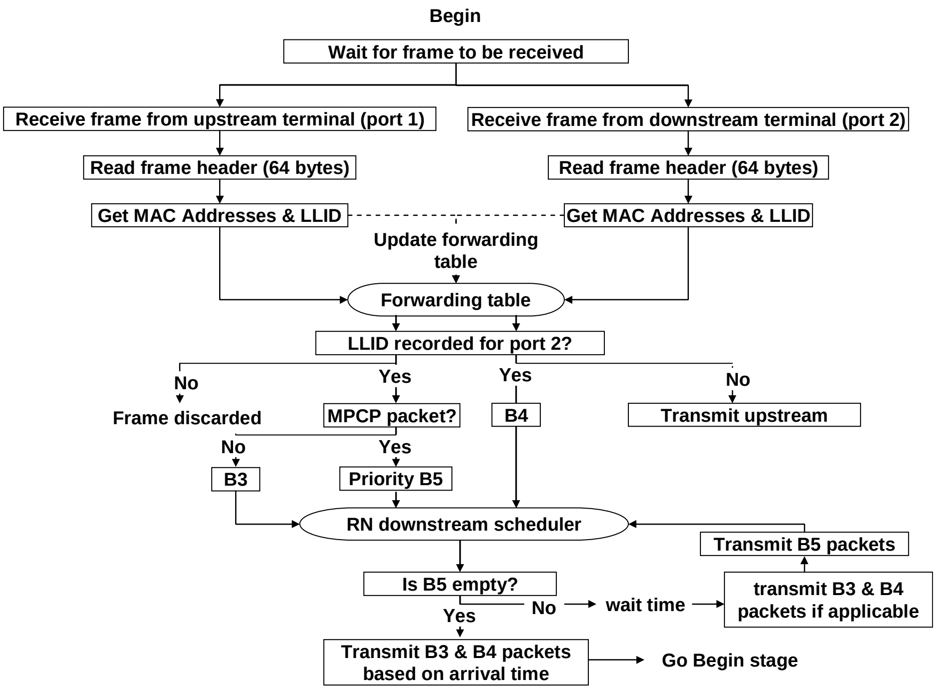

Fig. 4.10: Active RN traffic redirecting flowchart.

4.4. Simulation Set-up

A discrete simulation of the proposed architecture was conducted using MATLAB with the 1:2:16 architecture (two subnets with each connected to an active RN as shown in Fig. 4.8). Two sets of simulation were conducted, one with RNs and one without RNs. It is assumed that the amount of traffic transmitted from and to the four subnets is equal. Therefore, the performance of using and without using the RN can be evaluated by simply comparing the network performance of subnet 1. Furthermore, we assumed static bandwidth allocation (SBA) is used for simplicity as the main purpose of the simulation work is to evaluate the performance of utilising the active RN in EPON. The local intra-subnet traffic (traffic destined to own subnet) was varied from 5% to 25% of the total traffic and a similar amount of traffic is assumed from the local subnet to other subnets (local inter-subnet traffic).

Parameters	Value
Number of ONUs	16
Link speed (up/down)	1 Gb/s
Transmission cycle time	2 ms
Inter-frame gap (IFG)	96 ns
Laser on/off	512 ns
Automatic Gain Control (AGC)	400 ns
Clock and Data Recovery (CDR)	400 ns
Code Group Align	32 ns
Distance OLT to RN	58 km
Distance RN to ONUs	2 km
Shared buffer size	50 kBytes
RN processing delay	100 µs
Packet size	64-1518 bytes (uniformly distributed)

Table 4.2: Remote Node 1 (refer to Fig. 4.8) forwarding table list.

The simulation parameters are summarised in Table 4.2. The simulation is built using self-similar synthetic traffic generation with packet sizes uniformly distributed between 64 and 1518 bytes [29-31]. The link capacity is assumed as a 1G-EPON (1 Gb/s). The distance from OLT to each ONUs is set at 60 km (since the active RN is built on top of a repeater which extends the distance of the PON up to 60 km [17]). The transmission cycle time is 2 ms due to delay requirement for voice traffic in access network [4]. The processing delay for pass-through traffic at the RN is set at 100 μs (half of the OLT delay).

4.4.1. RN frame loss rate

As shown in Fig. 4.9, the buffers represent important elements in the RN to store downstream frames pending transmission (B3), intra-subnet frames (B4) and upstream and downstream traffic (B1 and B2) while the frame header is being processed. In the simulation, the total buffer size is set at 50 kBytes with first-in-first-out (FIFO) structure. However, the maximum total buffer size (B1, B2, B3 and B4) at every different traffic load and local intra-subnet traffic percentage, are recorded in Fig. 4.11.

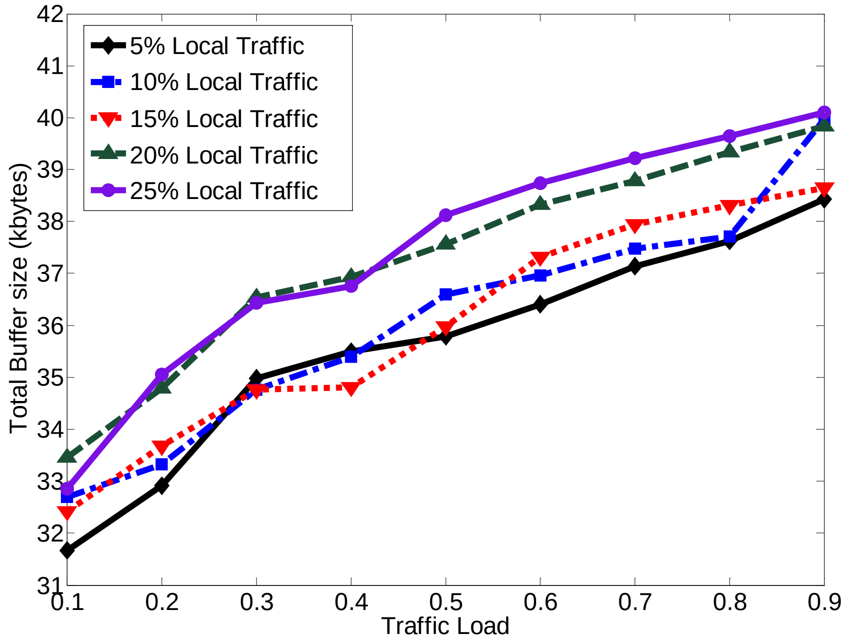

Fig. 4.11: Maximum total buffer size in an active RN (B1 + B2 + B3 + B4).

Overall, there is no one particular period where the maximum buffer size is larger than 42 kBytes. Therefore, the total buffer size in the simulation is set at 50 kBytes and hence there is no frame loss in the RN. It is important that the active RN implementation will not impact the current working EPON system. If there is a frame loss in the active RN, the ONU or OLT will need to retransmit the lost frames and consequently, the network efficiency will decrease, which is not desired. Therefore, keeping the frame loss rate to negligible is crucial in the active RN with EPON implementation. It is also noted that maximum buffer size for B5 is not included in the Fig. 4.11 since B5 is only used for MPCP frames and it has the highest priority. Therefore, buffer B5 will not grow in size and hence almost negligible.

4.5. Simulation and Theoretical Analysis

In this section the simulation results on average packet transmission delay for both local intra-subnet traffic and external traffic will be presented. The upstream external traffic delay from the ONUs will not be shown graphically due to the reason that the traffic will suffer a fix processing delay of approximately 100 μs as discussed in section 4.3 regardless of the traffic load due to processing. Following the simulation results, theoretical analysis and estimations on packet transmission delay for both local intra-subnet traffic and external traffic will be carried out to support the simulation results and to prove the feasibility of the scheme.

4.5.1. Simulation results

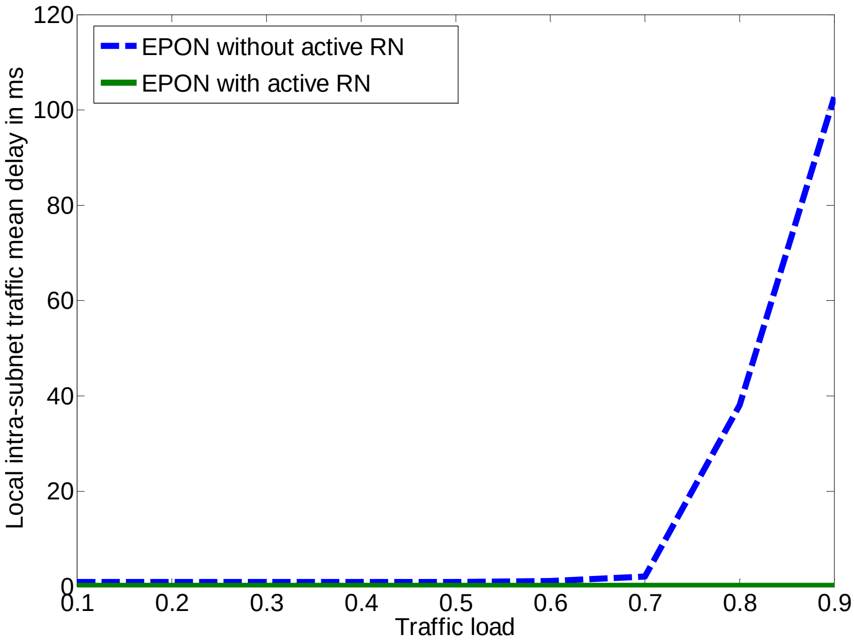

Fig. 4.12: Local intra-subnet traffic delay for EPON incorporated active remote repeater node with layer two forwarding for local traffic percentage of 15%.

Fig. 4.12 and Fig. 4.13 show the simulation result of EPON with active RN architecture for local intra-subnet traffic amount of 15% of overall upstream traffic. Fig. 4.12 represents the local traffic delay and show that the delay difference between EPON architecture without RN and with RN becomes larger when the local traffic percentage is increasing (which means the reduction in latency increase). In general, the advantage of using the active RN in EPON starts to become significant when the traffic load surpass 0.7 and further increases as the amount of local intra-subnet traffic increases. This is due to the fact that the OLT in EPON without active RN architecture does not have sufficient time slots to transmit the redirecting traffic when the traffic load is high; however with the use of active RN, this limitation is eliminated due to redirection of local traffic at the active RN utilising the freed time slots due to downstream filtering.

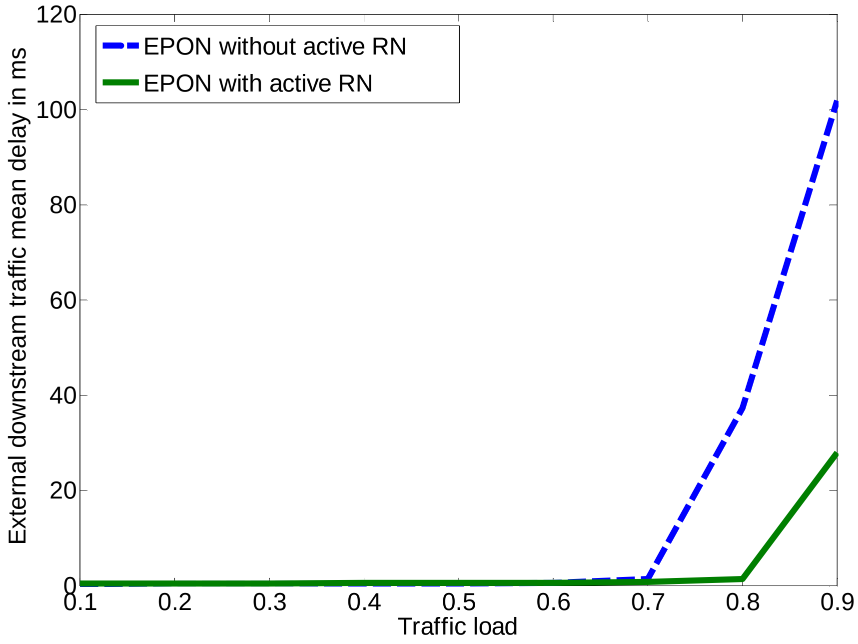

Fig. 4.13: External downstream traffic delay for EPON incorporated active RN with layer two forwarding for local traffic percentage of 15%.

The external downstream traffic delay for local intra-subnet traffic amount of 15% of overall upstream traffic is shown in Fig. 4.13. The reduction in delay increases with the traffic load and as the amount of local intra-subnet traffic increase. These results are similar to the local traffic delay except at a relatively higher load. When the traffic load is high at 0.8 or 0.9, the downstream delay with the active RN in EPON will also increase due to unavailability of sufficient timeslots to transmit all the downstream and local inter-subnet traffic at the OLT end (note that same amount of inter-subnet traffic as intra-subnet traffic is generated by the ONUs).

The simulations were carried out for the other four different local intra-subnet traffic amounts (5%, 10%, 20% and 25%) to evaluate the delay improvement due to variety of local intra-subnet traffic scenarios. The difference in mean delay for EPON with active RN and without active RN for local intra-subnet traffic (mean delay of without active RN – mean delay of with active RN) is shown in Fig. 4.14. The figure shows the delay difference becomes larger (which means the improvement becomes larger when RN is implemented in the EPON) when the local traffic percentage is increasing. In general, at lower local intra-subnet traffic percentage, which means less traffic needed to be redirected back to the subnet, there will be negligible improvement when the network traffic load is less than 0.7. The advantage of using the active RN in EPON starts when traffic load surpasses 0.6 for large amount of local intra-subnet traffic; and 0.7 for small amount of local intra-subnet traffic. This is due to the reason that the OLT in EPON without active RN has sufficient time slots to transmit the redirected traffic when the traffic load is low.

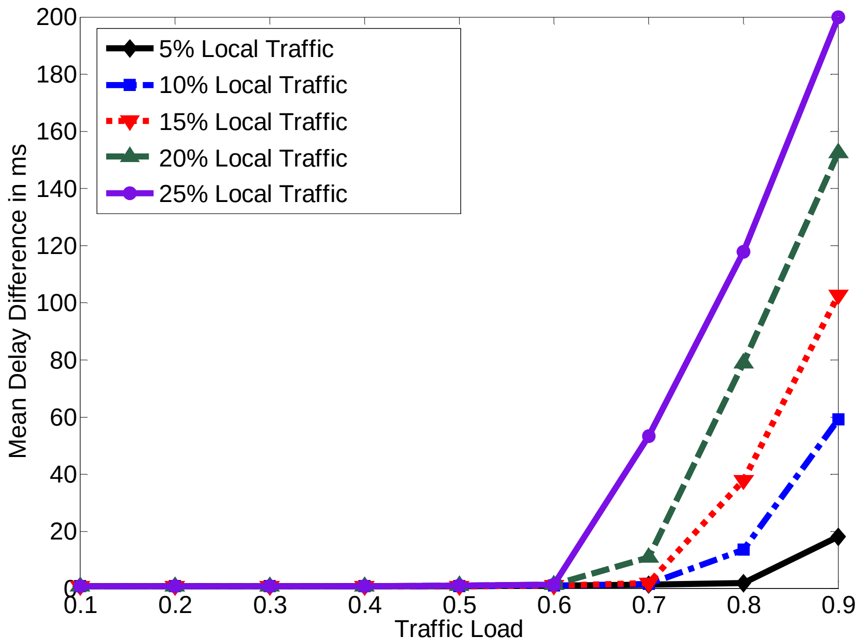

Fig. 4.14: Simulation results on the mean delay improvement with active RN in EPON implementation for local intra-subnet traffic (mean delay of without RN – mean delay of with RN).

When the traffic load of higher than 0.6, the delay improvement of using the active RN becomes significant as the EPON without active RN will no longer be able to transmit the accumulated external and local intra-subnet traffic in one transmission cycle. Also, the improvement becomes larger when the amount of redirected traffic increases. When the whole upstream traffic contains 25% of the local intra-subnet traffic, the mean delay difference between EPON without active RN and with active RN can be up to 200 ms when the network traffic load is high at 0.9. This proves one advantage of using the proposed architecture at high traffic load, which is the significant decrease in latency for local intra-subnet traffic due to the reason that buffering of local intra-subnet traffic in the OLT is no longer needed.

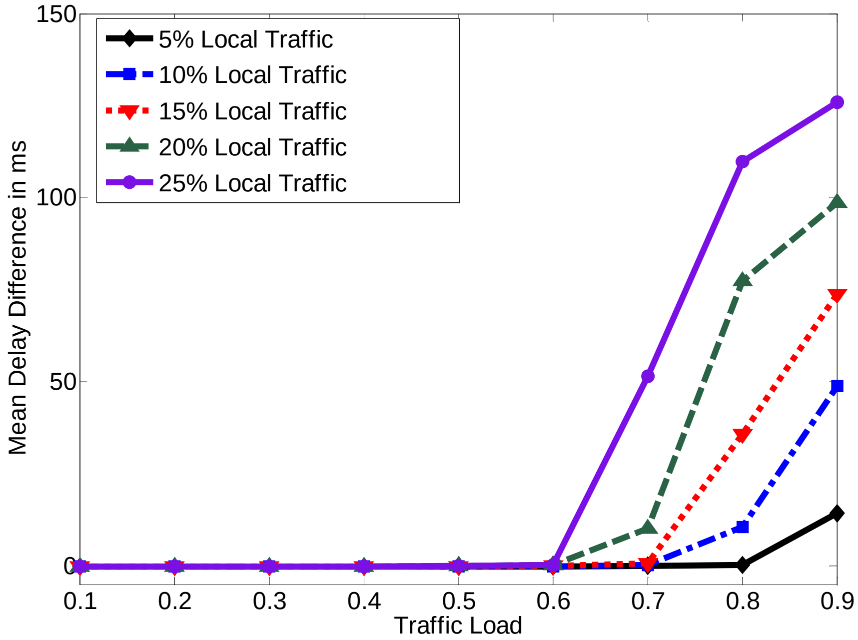

Fig. 4.15: Simulation results on mean delay improvement with active RN in EPON implementation for downstream traffic from OLT (mean delay of without RN – mean delay of with RN).

The difference in mean delay between EPON with active RN and without active RN for downstream traffic from OLT is shown in Fig. 4.15. When the amount of local intra-subnet traffic increases, the mean delay difference becomes larger. This is a similar result compared to Fig. 4.12. At traffic load of less than 0.6 or 0.7 for large or small amount of local intra-subnet traffic respectively, the downstream transmission window is adequate to carry the total accumulated external and local redirecting traffic. When the amount of local intra-subnet traffic needed to be redirected back to the subnet is small, significant improvements only occur when the network traffic load is high at 0.8 to 0.9. However, when the amount of local intra-subnet traffic is large at 25% of all upstream traffic, the improvement from using the active RN becomes significant at traffic load larger than 0.6. The delay improvement of downstream traffic can be up to 140 ms at high network traffic load (0.9). Since the local intra-subnet traffic does not require to be redirected at OLT, this creates free time slots to transmit buffered external network traffic at OLT and hence reduce the delay of downstream traffic. This result again proves another benefit of implementing EPON with this active RN architecture.

The simulation has shown the network performance is improved for both upstream and downstream. With the active RN architecture of EPON, the network has the ability to redirect the local intra-subnet traffic and filter unwanted frames without modifying the functionality of EPON. This improves the downstream capacity since local intra-subnet traffic is no longer required to be sent to the OLT. Furthermore, the local intra-subnet traffic which is redirected at the active RN will have much lower delay compared to the network structure without active RN as this traffic will no longer traverse through the feeder length and use up a portion of OLT buffer storage. These may allow the active RN architecture of EPON to accommodate more users such as 128 or 256 ONUs and also increase the reach of the optical network due to the regeneration of the traffic. The capacity improvement per user or the increase in number of ONUs due to the efficiencies of the proposed active RN architecture will be presented in the next chapter.

4.5.2. Theoretical analysis

In this section, theoretical estimations on maximum packet delay for both local intra-subnet traffic and external downstream traffic are discussed. Table 4.3 describes the definition for various parameters, which will be used in this section.

The reason that maximum packet delay will be shown here instead of average packet delay is that the theoretical estimation method calculates the amount of left over data stream (Mb/s) that is required to be buffered due to insufficient bandwidth within the current transmission cycle. This buffered data stream will introduce delays that are compared to the EPON link capacity of 1 Gb/s. However, during network simulation used in previous section, thousands of data packets have been generated at a given period of time. Some amount of packets will not experience delay in the network while the others will experience different delays due to burstiness of Ethernet frames. Also, due to bursty Ethernet frames, some packets will be scheduled to be transmitted beyond the network simulation period and these delays will not be taken in account. Furthermore, due to the reason that SBA is assumed in the simulation, some ONUs will experience high traffic load while some ONUs will have no traffic to transmit in a particular timeslot. As a consequence, the simulation results of maximum packet delay for local intra-subnet traffic and external downstream traffic will be shown to compare with theoretical estimated maximum packet delay.

PARAMETERS	DEFINITION
N	Number of ONUs
$C_{capacity}$	Link capacity (Mb/s)
α	Local traffic percentage (%)
$L_{traffic}$	Traffic load (0.1 – 0.9)
T_{ds}	Total downstream traffic at OLT (Mb/s)
t_{local}	Maximum local traffic delay (s)
t_{ds}	Maximum external downstream traffic delay (s)

Table 4.3: Definition of parameters for theoretical analysis on EPON incorporated active remote repeater node with layer two forwarding scheme.

The link capacity of an EPON system is set to be 1 Gb/s, $C_{capacity}$ = 1 Gb/s and the number of ONU, N is set as 16 to be identical to simulation setup discussed in previous section. According to the simulation setup, the local intra-subnet traffic, α has the value varied from 5% to 25% of $L_{traffic}$ since $L_{traffic}$ will represent the traffic load for both upstream and downstream. The total traffic that is needed to be redirected at the OLT, γ, is proportional to 2 times α for EPON without active remote node since both intra-subnet and inter-subnet traffic will route through the OLT. However, for EPON with active RN architecture, the total local traffic that is required to go through the OLT is proportional to α since the local intra-subnet traffic will be routed through the active RN as shown below:

$$\gamma = \begin{cases} \alpha \times L_{traffic} \times C_{capacity} & \text{for EPON with active RN} \\ 2\alpha \times L_{traffic} \times C_{capacity} & \text{for EPON without active RN} \end{cases}. \quad (4.1)$$

Hence the total amount of traffic that is needed to be transmitted downstream from the OLT is, $T_{ds} = \gamma + \left(L_{traffic} \times C_{capacity}\right)$ Mbit per observation period (s). Without active forwarding in conventional EPON, the local traffic will be mixed with the external traffic at the OLT. Therefore the estimations of maximum delays for local intra-subnet traffic and external downstream traffic for EPON without active RN will be similar and are calculated through:

$$t_{local} = t_{ds} = \frac{T_{ds} - 1\,Gbit}{C_{capacity}} \text{ (s).} \tag{4.2}$$

However, if the active RN is in place to redirect local intra-subnet traffic, the estimated maximum local intra-subnet traffic delay, t_{local} is assumed to be negligible due to the reason that the overall downstream traffic is shared among all ONUs equally. In a two-split EPON network, almost half of the downstream packets will be discarded and hence it will always create enough timeslot to transmit the local intra-subnet traffic. The only possible delay parameters that take into account will be the propagation delay from the ONU to the active RN and a fixed processing delay at the RN. However, the summation of these delays parameters will be in μs range. Therefore, it is almost negligible compared to ms delay range that is caused by traffic re-routing through the OLT. As a consequence, the external downstream traffic delay can be determined through equation (4.2). However, the total downstream traffic amount T_{ds} will be less compared to EPON without active RN architecture due to equation (4.1).

The theoretical estimation curves of five different local traffic percentage scenarios, α = {5%, 10%, 15%, 20%, 25%} for the maximum delays of local intra-subnet and external downstream traffic are shown in Figs. 4.16 and 4.18. Fig. 4.16 shows the theoretical estimation results of $t_{local}(\text{without RN}) - t_{local}(\text{with RN})$ while Fig. 4.18 shows the theoretical estimation results of $t_{ds}(\text{without RN}) - t_{ds}(\text{with RN})$. These two figures show similar curves compared to Fig. 4.17 and Fig. 4.19 (which are the simulation results on maximum delay difference using the same simulation parameters for Fig. 4.14 and 4.15) with small differences. For example, at high traffic load of 0.9 and local traffic percentage of 20%, the estimated maximum delay difference for both local intra-subnet traffic and external downstream traffic are 250 ms and 175 ms. However, Fig. 4.17 and Fig. 4.19 give the values of 300 ms and 200 ms. These differences are due to the infinite variance of Pareto distribution in the self-similar traffic generation [31]. This infinite variance causes the aggregated load to fluctuate considerably. The generated traffic that is used for Fig. 4.14, Fig. 4.15, Fig. 4.16 and Fig. 4.19 may vary from 0 to ±50 Mb/s and results in up to ±50 ms delay variation in the mean delay and maximum delay estimations. Furthermore, setting a longer simulation period will improve the accuracy of simulation results but it is time consuming and powerful computers are needed.

Nevertheless, the curves show in Fig. 4.16 and Fig. 4.18 tend to have similar attributes compared to Fig. 4.17 and Fig. 4.19. As the traffic load and local traffic percentage increase, the improvement of local intra-subnet traffic and external downstream traffic will increase. These results show the practical simulation results compared very favourably to the values estimated through theoretical calculations.

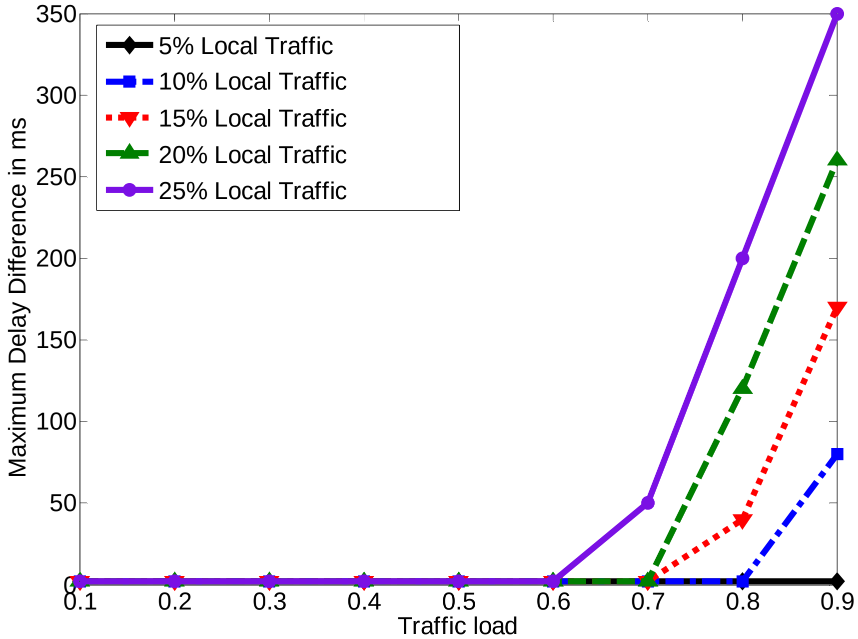

Fig. 4.16: Theoretical estimation on the maximum delay difference with RN in EPON implementation for local intra-subnet traffic (maximum delay of without RN – maximum delay of with RN).

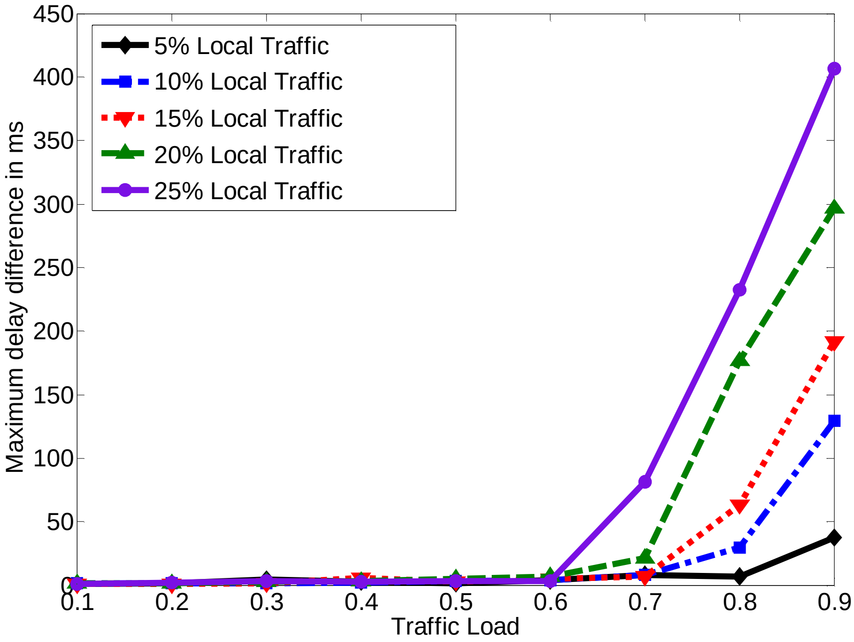

Fig. 4.17: Simulation results on the maximum delay difference with RN in EPON implementation for local intra-subnet traffic (maximum delay of without RN – maximum delay of with RN).

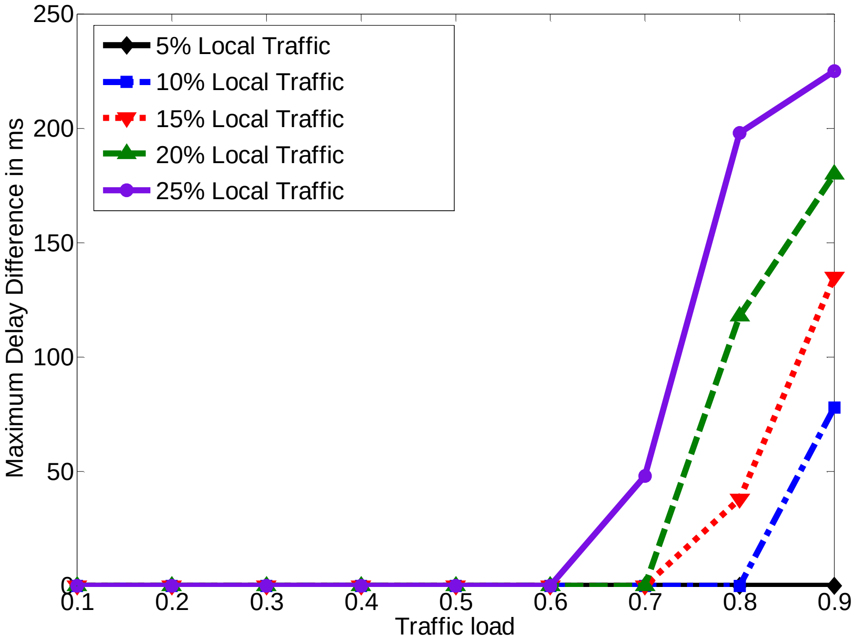

Fig. 4.18: Theoretical estimation on the maximum delay difference with RN in EPON implementation for external downstream traffic (maximum delay of without RN – maximum delay of with RN).

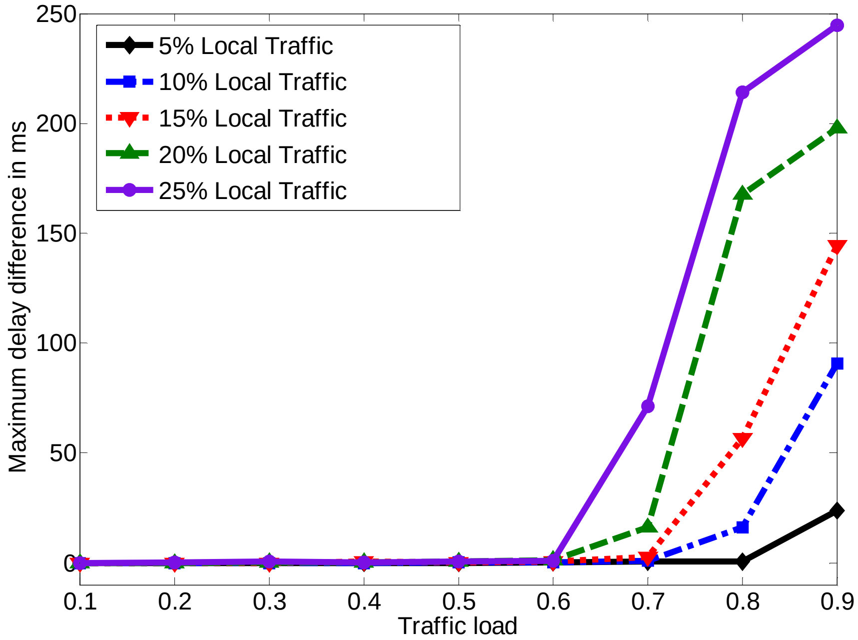

Fig. 4.19: Simulation results on the maximum delay difference with RN in EPON implementation for external downstream traffic (maximum delay of without RN – maximum delay of with RN).

4.6. Conclusion

The chapter presented a simple hybrid active EPON scheme with the implementation of repeater based active RN to improve the network performance. The active RN listens to all EPON frames to gather layer two (or MAC) network information and forms a forwarding table containing MAC and LLID addresses attached to the upstream and downstream transmission ports. This forwarding table is used to redirect and filter frames.

The proposed architecture of using the active RNs in EPON requires no impact on existing EPON protocols such as MPCP and DBA and no modification on OLT and ONU. Fixed processing delay of the RN is included in initial ranging process. DBA and normal frames will only be used for information gathering and transmitted accordingly without modification. However, improvement of using DBA in EPON with RN scheme is an interesting research topic and will be presented in Chapter 6. Moreover, MPCP is important in this architecture due to the reason that the initial layer two forwarding table in the active RN is built based on the initial auto-discovery frames listening when the ONU is registering into the network. Therefore, the active RN in EPON architecture works in conjunction with the MPCP protocol.

In section 4.5, both simulation and theoretical analysis have been carried out to show the improvement of the overall downstream and local traffic delay at high traffic load and large local intra-subnet traffic in the network. This simple architecture helps to increase the number of subscribers and the reach of EPON. In the next chapter, we extend this work to investigate the bandwidth bottleneck issue in long reach and high split-ratio EPON system. The use of active RN with layer two forwarding EPON will be used to improve the downstream data rate per user compared to conventional EPON system.

4.7. References

[1] B. Skubic, J. Chen, J. Ahmed, L. Wosinska, B. Mukherjee, "A comparison of dynamic bandwidth allocation for epon, gpon, and next-generation tdm pon – [topics in optical communications]," *IEEE Commun. Mag.*, vol. 47, no. 3, pp. S40-S48, Mar. 2009.

[2] C. M. Assi, Y. Ye, D. Sudhir, M. A. Ali, "Dynamic bandwidth allocation for quality-of service over Ethernet PONs," *IEEE J. Sel. Areas* Commun., vol. 21, no. 9, pp. 1467-1477, Nov. 2003.

[3] H-J. Byun, J-M. Nho, J-T. Lim, "Dynamic bandwidth allocation algorithm in Ethernet passive optical networks," *IEE Electron. Lett.*, vol. 39, no. 13, pp. 1001-1002, Jun. 2003.

[4] G. Kramer, B. Mukherjee, G. Pesavento, "IPACT a dynamic protocol for an Ethernet PON (EPON)," *IEEE Commun. Mag*. vol. 40, no. 2, pp. 74-80, Feb. 2002.

[5] I. S. Hwang, Z. D. Shyu, L. Y. Ke, C. C. Chang, "A novel early DBA mechanism with prediction-based fair excessive bandwidth allocation scheme in EPON," *Comp. Commun.*, vol. 31, no. 9, pp. 1814-1823, Jun 2008.

[6] M. P. McGarry, M. Reisslein, and M. Maier, "Ethernet Passive Optical Network Architectures and Dynamic Bandwidth Allocation Algorithms," *IEEE Commun. Surveys and Tutorials*, vol. 10, no. 3, pp. 46-60, 2008.

[7] G. Kramer, "Ethernet Passive Optical Networks," *McGraw-Hill Prof.*, 2004, ISBN: 0071445625.

[8] G. Kramer, B. Mukherjee, N. Singhal, A. Banerjee, S. Dixit, and Y. Ye, "Fair queing with service envelopes (FQSE): a cousin-fair hierarchical scheduler for subscriber access networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 8, pp. 1497-1513, Oct. 2004.

[9] A. Banerjee, G. Kramer, B. Mukherjee, "Fair sharing using service-level agreements (SLAs) for open access in EPON," *Proc. IEEE International Conf*erence on *Communication*, vol. 3, pp. 1858-1862, May 2005.

[10] A. Shami, X. Bai, N. Ghani, C. M. Assi, H. T. Mouftah, "QoS Control Schemes for Two-Stage Ethernet Passive Optical Access Networks," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 8, pp. 1467-1477, Aug. 2005.

[11] Riverstone Networks, "FTTP Shootout – Active Ethernet vs PON," *Riverstone Networks Inc. White Papers*, 2004.

[12] J. S. Shaik, N. R. Patil, "FTTH Deployment Options for Telecom Operators," *Sterlite Optical Tech. Ltd White Papers*.

[13] V. Vittore, "Ethernet gets active in its pitch against PON," *Telephony Online*, Sep. 2004.

[14] Allied Telesyn, "Active vs PON FTTx Technology Choices," *Allied Telesyn Tech. Brief*, 2004.

[15] I. Gillath, "Making the Samrt Decision: Active Ethernet FTTH," *Telco Systems*, Jan. 2008, available online at http://www.broadbandproperties.com

[16] C. A. Chan, M. Attygalle, A. Nirmalathas, "Active Remote Node with layer Two Forwarding for Improving Performance of EPON," in *Proc. IEEE Global Telecommunications Conference*, pp. 1-5, Nov. 2008.

[17] A. V. Tran, C.-J. Chae, R. S. Tucker, "Low-cost and scalable passive optical network architecture using remote repeater," *IEE Electron*. *Lett*. vol. 42, no. 10, pp. 589-591, May 2006.

[18] A. V. Tran, C.-J. Chae, R. S. Tucker, "Cascadability performance of remote-repeater-based FTTP systems," *IEE Electron*. *Lett*. vol. 42, no. 24, pp. 1418-1420, Nov. 2006.

[19] A. V. Tran, C.-J. Chae, R. S. Tucker, "Cost-effective fiber-to-the-home system using remote repeater," in Proc. Optical Fiber Communication Conf. (OFC '06), OFC 2006, Mar. 2006.

[20] N. Nadarajah, A. V. Tran, C.-J. Chae, "10 Gb/s upgrade for high-split and long reach PON using remote repeater," in *Proc. Opto-Electronics and Communications Conference*, Jul. 2008.

[21] IEEE 802.3 ah EFM standard, (part of IEEE std 802.3), available online at http://standards.ieee.org/getieee802/

[22] A. E.-D. Mady, A. Tonini, "A VHDL implementation of onu auto-discovery process for EPON," in *Proc. International Conference on Networking and Media Coverage*, pp. 36-41, Mar. 2009.

[23] J. Wang, L. Sun, X. Jiang, Z. Wu, "IGMP snooping: a VLAN-based multicast protocol," in *Proc. IEEE International Conference on High Speed Networks and Multimedia Communication*, pp. 335-340, Jul. 2002.

[24] V. Ponnusamy, E. K. Karuppiah, R. Abdullah, "Anycast group membership management protocol," in *Proc. Asia-Pacific Conference on Communications*, vol. 3, pp. 1052-1056, Sep. 2003.

[25] Y. K. Kwang, H. K. Pung, Robin, "Managing group operations in IP multicast," in *Proc*. *Fourth Pacific Rim Conference on Multimedia Information, Communications and Signal Processing*, vol. 1, pp. 423-427, Dec. 2003.

[26] M. J. Castelli, "LAN Switching first-step," Chapter 4, *Cisco Press*, 2004, ISBN: 9781589201004, available online at http://www.ciscopress.com/articles/

[27] K. Clark, K. Hamilton, "Cisco LAN Switching (CCIE Professional Development series)," *Cisco Press*, 1999, ISBN: 1578700949.

[28] P. Miller, M. Cummins, "LAN Technologies Explained," Digital Press, 2000, ISBN: 1555582346.

[29] M. S. Taqqu, W. Willinger, R. Sherman, "Proof of a fundamental result in self-similar traffic modelling," *ACM/SIGCOMM Computer Commun*. *Rev*. vol. 27, pp. 5-23, 1997.

[30] W. Willinger, M. S. Taqqu, R. Sherman, D. V. Wilson, "Self-similarity through high-variability: statistical analysis of Ethernet LAN traffic at the source level," *IEEE ACM Trans*. *on Networking*, vol. 5, no. 1, pp. 71-86, Feb. 1997.

[31] W. E. Leland, M. S. Taqqu, W. Willinger, D. V. Wilson, "On the self-similar nature of Ethernet traffic (extended version)," *IEEE ACM Trans*. *on Networking*, vol. 2, no. 1, pp. 1-15, Feb. 1994.

5 Active RN for Improving Downstream Performance in EPON

5.1. Introduction

The growing demand for broadband services combined with the improved economics of broadband access network technologies have resulted in passive optical network (PON) based broadband network architecture to evolve from a technology for the greenfield deployment into a more cost-effective access network of choice for both tele-communications service providers (SPs) and network operators [1]. With widespread deployment of PON, the research focus has shifted to the scalability of PON such as longer reach and higher split-ratio.

As discussed in Chapter 2, the PON deployment is limited to split-ratio of less than 64 and network reach in the order of 20 km as stipulated by the most popular PON standards such as Ethernet PON (EPON) and gigabit PON (GPON) [2-4]. In Chapter 4, the active remote repeater node (RN) with Open System Interconnection (OSI) layer two forwarding scheme is proposed to be used on a conventional EPON with only 16 ONUs. However, higher split-ratio can increase the benefits of a PON by lowering cost through sharing the OLT optics, electronic and feeder fibre among a larger number of users; more efficiently utilising the head end rack space for higher density OLT; and simplifying the fibre management at the head end [5-7]. Furthermore, the high split-ratio PON, which accommodates more users within each PON makes the network become more flexible and be able to address the market that consist of various bandwidth intensive services. Increasing the reach of the network will lead to a reduction in the number of central office (CO) premises located close to the customers and allow the network operators to consolidate multiple COs in more conveniently located facilities for easier management. However, increasing customer number in the EPON system reduces the data rate available per customer due to the link capacity limit of 1 Gb/s.

This chapter discusses the use of active RN with layer two forwarding scheme in EPON to either increase the split-ratio (number of users) or to improve the downstream bandwidth per user in high split-ratio, long reach access network. The rest of the chapter is organised as follows: Section 5.2 discusses the technique for realising long reach and high split-ratio optical access system and the issue of bandwidth bottleneck in large scale access networks. Section 5.3 gives a summary of important active forwarding RN functional details as discussed in Chapter 4. Section 5.4 demonstrates the simulation setup of long reach and high split-ratio EPON using active RN with layer two forwarding. Section 5.5 presents the simulation results in four parts. Important parameters such as total buffer size and traffic delay analysis are discussed in sections 5.5.1 and 5.5.2 to show consistency as compared to 16 ONUs EPON with active forwarding RN results in Chapter 4. Section 5.5.3 demonstrates the use of active forwarding RN to improve the downstream data rate per ONU while section 5.5.4 shows the use of active forwarding RN to increase the number of ONU in the network while keeping the downstream external incoming traffic data rate and delay equal to conventional EPON without active forwarding RN. Section 5.6 discusses the theoretical analysis on results showed in sections 5.5.1 and 5.5.2. Finally section 5.7 summarises the overall chapter.

5.2. Techniques for Realising Long Reach and High Split-ratio EPON

Although the benefits of increasing the distance and split-ratio of the PON as discussed in the previous section can be attractive to SPs, the optical power budget remains a major challenge. In Chapter 2, the use of forward error correction (FEC) technique [8-9] and optical amplifier [10-14] for achieving higher split-ratio and longer reach have been discussed in detail. In this section, the summary of these techniques will be presented to discuss the bandwidth limitation as the result of higher split-ratio has been achieved. The FEC technique that is implemented in PON can provide a coding gain of up to 7.8 dB at the bit-error-rate (BER) of 10^{-10} by trading off a reduction in bandwidth due to overhead depending on receiver type [8]. However, most of the FEC techniques induce latency due to the requirement of adequate code blocks before decoding. Furthermore, this approach suffers from increased cost and power consumption of the OLT [5].

Cascaded semiconductor optical amplifier (SOA) and Erbium-doped fibre amplifier (EDFA) has been used to extend PON reach to 100 km while supporting 2048 users as part of the SuperPON demonstration [10]. In this demonstration, optically amplified splitters by incorporating SOAs and EDFA based preamplifier were used to meet the necessary power budget to satisfy the extended reach and larger number of users connected to a single line termination [10]. In comparison to the SuperPON, British Telecom's Long-Reach PON has a reach of 100 km with a split-ratio of 1024 operating at a data rate of 10 Gb/s [11]. Although the Long-Reach PON's optical split-ratio is only a half of that in the SuperPON, it only requires six optical amplifiers for both upstream and downstream operation as opposed to 39 required by SuperPON [14].

In the photonic integrated extended metro and access network (PIEMAN) project [12], dense wavelength division multiplexing (DWDM) backhaul was incorporated to demonstrate a 32 wavelength network with 100 km reach. Each of the 10 Gb/s 32 wavelength channel was uniquely allocated to a PON with a split-ratio of 512, enabling the network to support 16,384 (32×512) users with an average bandwidth of around 20 Mb/s [14]. By using dynamic bandwidth assignment (DBA) mechanism and colourless ONUs operating at 10 Gb/s, each user could burst at 10 Gb/s [14]. An alternative proposal based on hybrid DWDM-time division multiplexing (DWDM-TDM) was also used to demonstrate long reach PON with a reach of up to 100 km, each working at different wavelengths to share the same fibre infrastructure [13]. This design demonstrated the combination of the extended reach of optically amplified PONs with the increased number of users enabled with DWDM.

The use of optical amplification to extend the reach and split-ratio of the optical access network often leads to reduced cost-effectiveness and may not be applicable to network scenarios where average bandwidth expectations need not be very high or initial subscription rates may be too low to warrant such higher cost base. Since the cost of optical amplifiers is shared among the subscribers in the network, if the initial subscription rate becomes high, the use of optical amplifiers with higher operational costs will increase the subscription cost per user. A PON architecture incorporating a RN was proposed to realise cost-effective network with long reach and higher split-ratio. This approach allows reduction in the cost of an optical network unit (ONU) by using a low-cost vertical cavity surface emitting laser (VCSEL) based transmitters while extending the feeder fibre reach and split-ratio of the access system [15-17]. This scheme can be easily adopted in EPON and was demonstrated to support 256 number of users with 60 km reach, albeit much smaller bandwidth per each user.

5.3. Active RN in Long Reach and High Split-ratio EPON

In general, all of the above projects evidenced that long reach and high split-ratio PON system can be practically realised to provide a more flexible and cost effective optical access network. However, when the network scales to support more customers, bandwidth efficiency in PON becomes a crucial issue since bandwidth per user is reduced with the increase of split-ratio. The current basic Internet services and applications, notably Web browsing and email, generally have modest peak bandwidth requirements. Furthermore, due to the reason that not all users are actively downloading or uploading at the same time, a high degree of bandwidth oversubscription is possible when aggregating traffic from multiple users [18]. However, Internet peer-to-peer (P2P) services and a significant larger amount of video services have increased bandwidth requirements dramatically during the recent years [19]. Streaming standard definition television (SDTV) quality service requires around 3 Mb/s sustained bandwidth per stream; while high definition TV (HDTV) will increase the demand to 8 Mb/s per stream [20]. Therefore, conventional 1 Gb/s EPON that is shared among larger amount of ONUs will decrease the data rate available per user to a critical level (3.9 Mb/s per ONU for 256 shared EPON) as shown in Fig. 5.1.

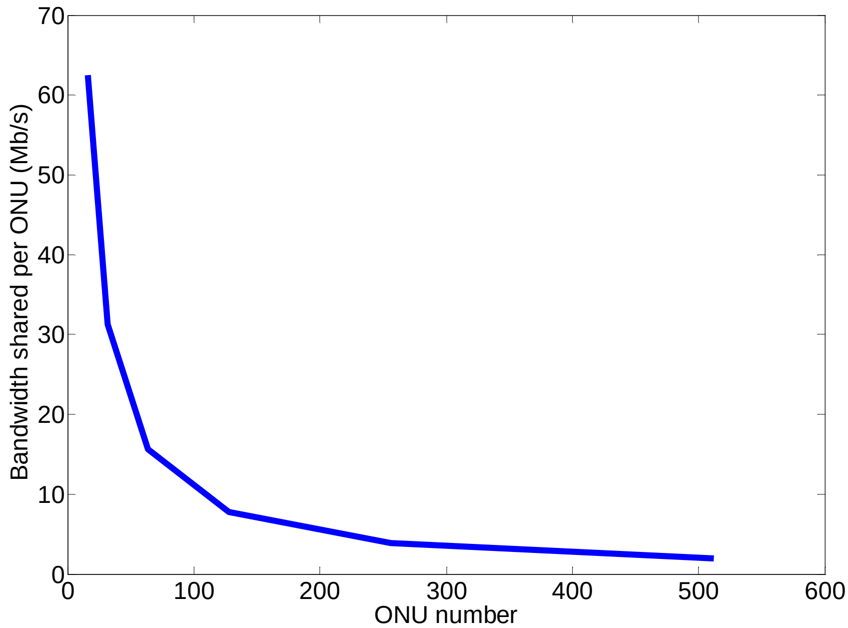

Fig. 5.1: Bandwidth shared per ONU in EPON against different ONU number.

As a consequence, we propose an active RN architecture with layer two forwarding function to improve the network performances in terms of delay, bandwidth per user or the number of ONUs [21]. In Chapter 4, a simple layer two forwarding technique implemented on top of the active RN is shown to achieve a large reduction in downstream and local intra-subnet traffic delays in 16 ONUs EPON. The active RN listens to header information of all incoming frames and forms the forwarding table to identify the medium access control (MAC) and logical link identity (LLID) addresses of the ONUs in the network that allows the active RN to filter and forward network traffic to appropriate ports [21, 24].

When upstream frames are received, the frame will be buffered to process the header reading up to 64 bytes (read destination MAC, LLID and source MAC addresses to determine the destination of the frame to be either redirected back to own subnet or transmitted upstream to OLT). The header reading process is also crucial in updating the forwarding table for knowing which ONU is connected to it. After the forwarding decision has been made to either redirect the frame back to the subnet (if the frame is destined to an ONU within the same subnet) or sending upstream to the OLT, the particular frame will be either transmitted back downstream (the frame will be buffered pending the downstream transmission) or upstream (if the frame's destination is to OLT or external network).

Same header reading process occurs to frame processing in downstream direction except the decision will be either sending the particular frame downstream or discard the frame if the destination of the frame is not within the subnet connected to the active RN. Also, the active RN downstream scheduler plays an important role to assure no delay variance occurs for multi-point control protocol (MPCP) frames (refer to Chapter 4 for more details on active forwarding RN functions). Imagine that all upstream local traffic between ONUs connecting the same active RN will be redirected downstream at the active RN. Hence more buffer space will be created at the OLT to accommodate external traffic from the Internet. This downstream traffic sequence will combined with redirected local traffic at the active RN to further increase the downstream data rate of EPON system. In the next section, two simulation setups will be discussed to analyse: i) Improving downstream bandwidth shared per ONU and ii) Improving the ONU number for scalability in EPON.

5.4. Simulation Setup

Discrete simulations of the proposed scheme were conducted using MATLAB. Two sets of simulation on the EPON system with active forwarding RN were completed; one to evaluate the downstream bandwidth shared among the ONUs and the other to evaluate the improvement in ONU numbers given equal ONU downstream external traffic data rate and packet delay to conventional EPON. In each simulation, two different networks were simulated; one with active RN and one without active RN to compare improvement of the implementation of EPON with active forwarding RN. It is assumed that the amounts of upstream and downstream traffic are split equally between the subnets. Therefore, the performance of using and without using the active RN can be evaluated by simply comparing the network performance of one subnet. We assumed static bandwidth assignment (SBA) is used for simplicity as the main purpose of the simulation work is to evaluate the performance of utilising active RN in large scale EPON system. This proposed scheme aims to improve the network performance when bandwidth bottleneck occurs at high traffic load. Therefore, SBA or fixed service is adequate to prove the feasibility of the scheme since it has similar delay characteristics at high traffic load compared to DBA [22, 23]. The local intra-subnet traffic (traffic destined for a destination within the same subnet) was varied from 5% to 20% of the total traffic and a similar amount of traffic is assumed to be from the local subnet to other subnets.

5.4.1. Simulation setup for evaluation of downstream bandwidth improvement

The simulation setup for this section is shown in Fig. 5.2. An EPON 1:2:64 architecture is used with each subnet having an active RN connecting 32 ONUs to give a total of 64 ONUs in the network. The simulation parameters are summarised in Table 5.1. The simulation is built using self-similar synthetic traffic generation with the packet size uniformly distributed between 64 and 1518 bytes [25]. The link capacity is assumed to be that of a 1Gb/s EPON. The distance from OLT to each ONUs is set at 60 km (since an RN incorporates a repeater which can extend the reach of the EPON to distances of up to 60 km [15-17]). The transmission cycle time is 2 ms due to delay requirement for voice traffic in access network [22]. The processing delay for pass-through traffic at the active RN is set at 100 μs and the

OLT processing delay is assumed to be 200 μs, which twice of the active RN's processing delay.

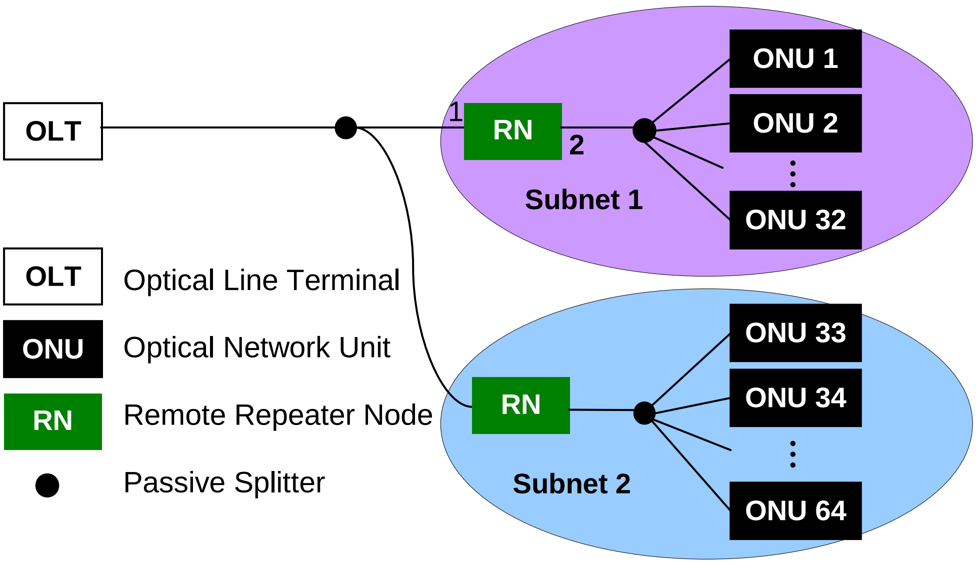

Fig. 5.2: EPON architecture for simulation setup of downstream bandwidth improvement test.

Parameters	Value
Number of ONUs	64
Link speed (up/down)	1 Gb/s
Transmission cycle time	2 ms
Inter-frame gap (IFG)	96 ns
Laser on/off	512 ns
Automatic Gain Control (AGC)	400 ns
Clock and Data Recovery (CDR)	400 ns
Code Group Align	32 ns
Distance OLT to RN	58 km
Distance RN to ONUs	2 km
Shared buffer size	50 kBytes
RN processing delay	100 μs
Packet size	64-1518 bytes (uniformly distributed)

Table 5.1: Simulation parameters.

5.4.2. Simulation setup for evaluation of ONU number improvement

The bandwidth improvement evaluation can be converted to an increase in the number of ONUs if the performances of the ONUs are kept constant. The same simulation as used in sub-section 5.4.1 can be modified to demonstrate the increase in ONU number instead of increasing traffic load. The same downstream load will be applied to each ONU while the ONU amount that is connected to both subnets is increased linearly during the simulation till a certain average downstream packet delay as same as EPON without active RN is achieved. The purpose of the simulation as shown in Fig. 5.3 is to evaluate the advantage of using active RN to increase the ONU number while keeping the downstream traffic delay and bandwidth per ONU the same. Fig. 5.3 shows the ONU number is increased to N until the same downstream delay as conventional EPON without active RN has been achieved.

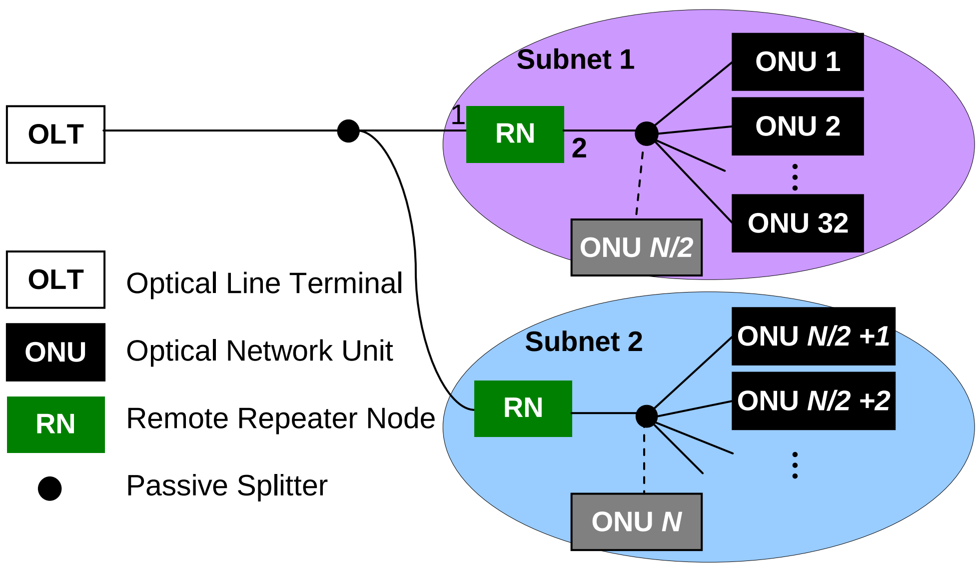

Fig. 5.3: EPON architecture for simulation setup of ONU number improvement test.

5.5. Simulation Results

In this section, the active RN frame loss rate will first be discussed highlighting the important role of the buffers in the active RN. It is essential to prove that same buffer size can be used to accommodate different network size compared to small scale EPON in Chapter 4. Hence, the external downstream traffic and local traffic delays results will be presented to prove similarity as compared to 16 ONUs EPON simulations in Chapter 4. This is important in the implementation of active forwarding RN to avoid a change in network characteristic if the active RN is used in network with different size.

5.5.1. Active RN frame loss rate in large scale EPON

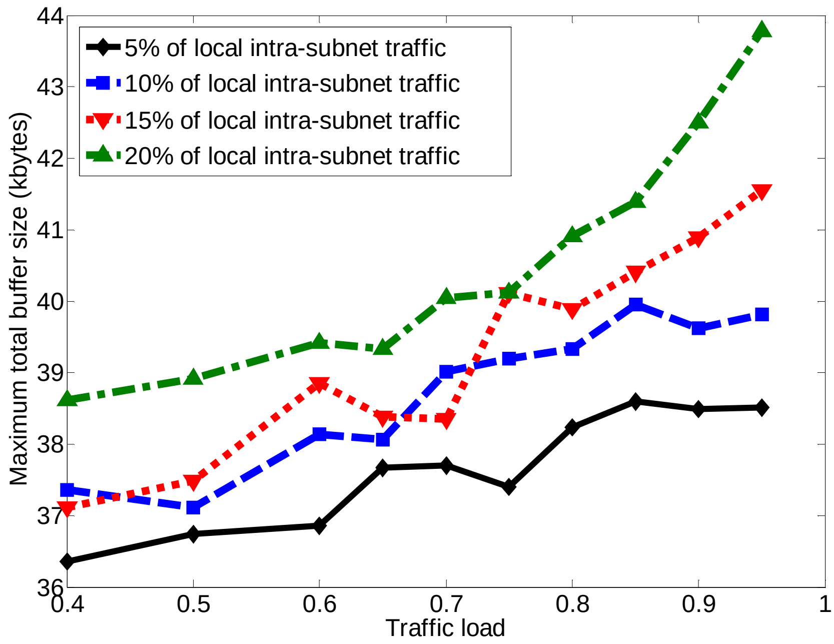

Fig. 5.4: Maximum total buffer size in active RN (B1 + B2 + B3 + B4).

As shown in Fig. 5.2 and Chapter 4, buffers represent important elements in the active RN to store downstream frames pending transmission (B3), intra-subnet frames (B4) and upstream and downstream traffic (B1 and B2) while the frame header is being processed. In the simulations for both downstream data rate improvement and ONU number improvement tests, the total buffer size is set at 50 kBytes with first-in-first-out (FIFO) queue structure. The maximum total buffer size (B1, B2, B3 and B4) corresponding to different traffic load and local intra-subnet traffic as a percentage of total upstream traffic are presented in Fig. 5.4.

Overall, there is no one particular period where the required maximum buffer size reaches a value larger than 44 kBytes. Therefore, the total buffer size in the simulation that is set to 50 kBytes would not cause any frame loss in the network. The network efficiency will decrease due to retransmission of frames due to frame loss. Therefore, it is important that the frame loss rate must be kept to a negligible level so that the RN implementation will not impact the underlying EPON system, which is crucial in the active RN design and implementation.

5.5.2. Delay improvement for EPON with active RN implementation

The difference in mean delay for EPON with and without active RN for local intra-subnet traffic is shown in Fig. 5.5 (a). The mean delay difference is calculated as the difference between the mean delay for the case of without active RN and the mean delay for the case of with active RN, similar to Chapter 4. The figure shows the delay difference between without and with active RN becomes larger (which means the reduction in latency becomes larger when active RN is implemented in the EPON) when the local traffic percentage is increasing. Similar to the mean delay results for small scale EPON in Chapter 4, at lower local intra-subnet traffic percentage; which means less traffic needed to be redirected back to the subnet, there will be negligible improvement when the network traffic load is less than 0.7. The advantage of using the active RN in EPON starts when traffic load surpass 0.6 for large amount of local intra-subnet traffic (15% and 20% of local intra-subnet traffic) and 0.7 for small amount of local intra-subnet traffic. This is due to the reason that the OLT in EPON without active RN has sufficient timeslots to transmit the redirecting traffic when the traffic load is low.

When the traffic load is higher than 0.6, the reduction in packet delay with the use of active RN becomes significant as the EPON without active RN will no longer be able to transmit the accumulated internet and local intra-subnet traffic in one transmission cycle. Also, the improvement becomes larger when the amount of redirected traffic increases. When the whole upstream traffic contains 20% local intra-subnet traffic, the mean delay difference between

EPON without and with active RN can be up to 190 ms when the network traffic load is at 0.95. The results are similar to that of 16 ONUs EPON system in Chapter 4, which shows that the use of active RN will result in similar performance upgrade regardless of the network size.

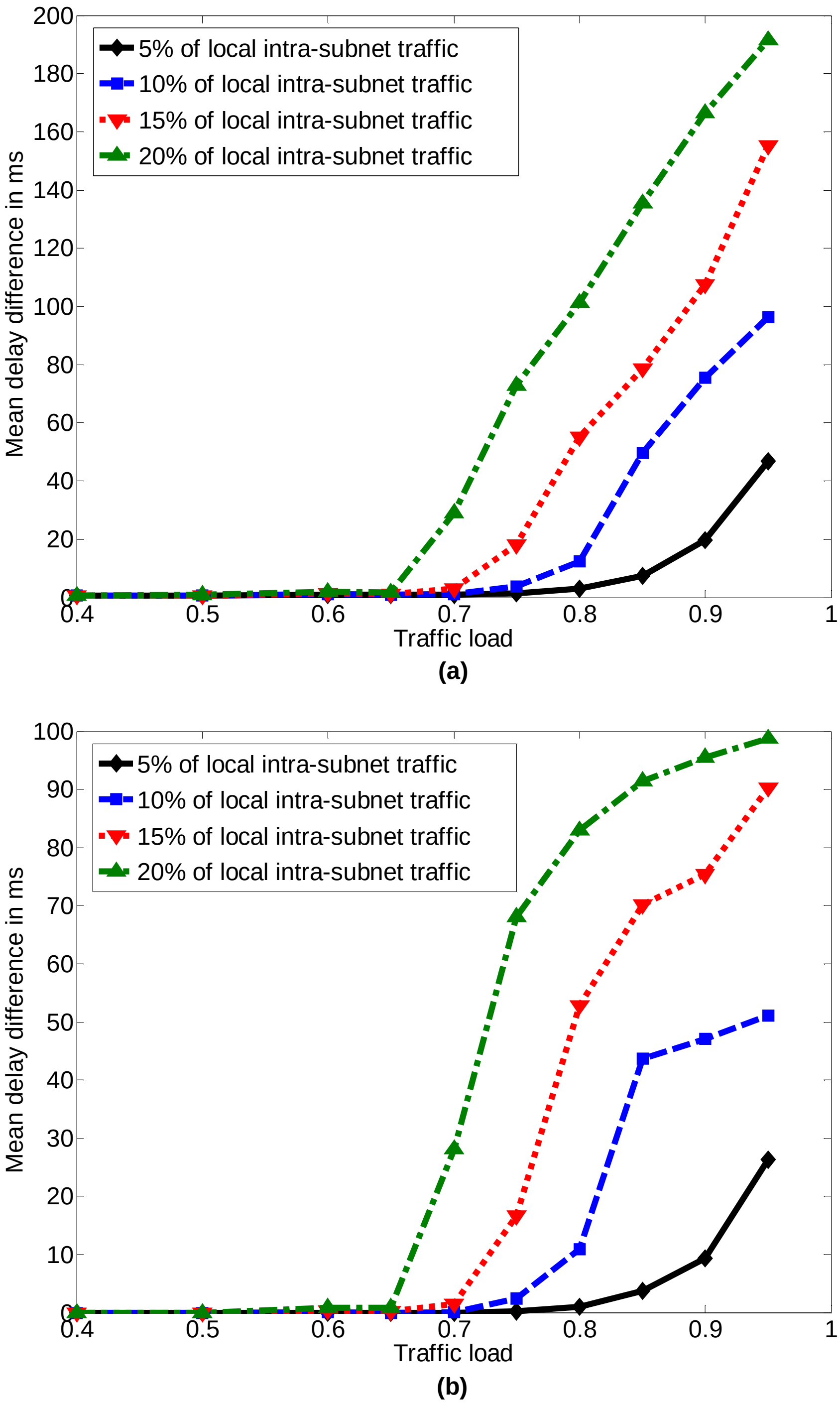

Fig. 5.5: Mean delay difference of using active RN in EPON for (a) local intra-subnet traffic and (b) downstream traffic from OLT.

The difference in mean delay between EPON with and without active RN for downstream traffic from OLT is shown in Fig. 5.5 (b). When the amount of local intra-subnet traffic increases, the mean delay difference becomes larger. This result is similar compared to Fig. 5.5 (a). At traffic loads of less than 0.6 or 0.7 for large or small amount of local intra-subnet traffic respectively, the downstream transmission capacity is adequate to carry the total accumulated internet and local redirecting traffic. When the amount of local intra-subnet traffic required to be redirected back to the subnet is small, significant improvements only occur when the network traffic load is high with the values from 0.8 to 0.9. However, when the amount of local intra-subnet traffic is large at 20% of all upstream traffic, the improvement of using the active RN becomes significant at traffic loads larger than 0.6. The delay improvement of downstream traffic can be up to 100 ms at high network traffic load of 0.95. Since the local intra-subnet traffic does not require to be redirected at OLT, this creates free timeslots to transmit buffered internet traffic at OLT and hence reduces the delay of downstream traffic.

The simulation results show the traffic delay characteristics for the use of active RN in high split-ratio EPON does not change compared to 16 ONUs EPON presented in the previous chapter. With the active RN architecture of EPON, the network has the ability to redirect local intra-subnet traffic and filter unwanted frames without modifying the functionality of EPON. This improves the downstream capacity since local intra-subnet traffic is no longer required to be sent to the OLT. Furthermore, the local intra-subnet traffic which is redirected at the active RN will have much lower delay compared to the network structure without active RN as this traffic will no longer traverse through the feeder length. These functionalities of the active RN make it a reliable network upgrade scheme regardless of the network size, which is desired in terms of management and efficiency.

5.5.3. Improvement in downstream data rate

In this sub-section, the use of EPON with active RN architecture to improve the downstream bandwidth for each ONU is discussed. The downstream bandwidth improvement for different local intra-subnet traffic amounts (from 5% to 20% of total traffic). We observe that as the traffic load and local intra-subnet traffic amount increase, the downstream bandwidth per ONU also increase.

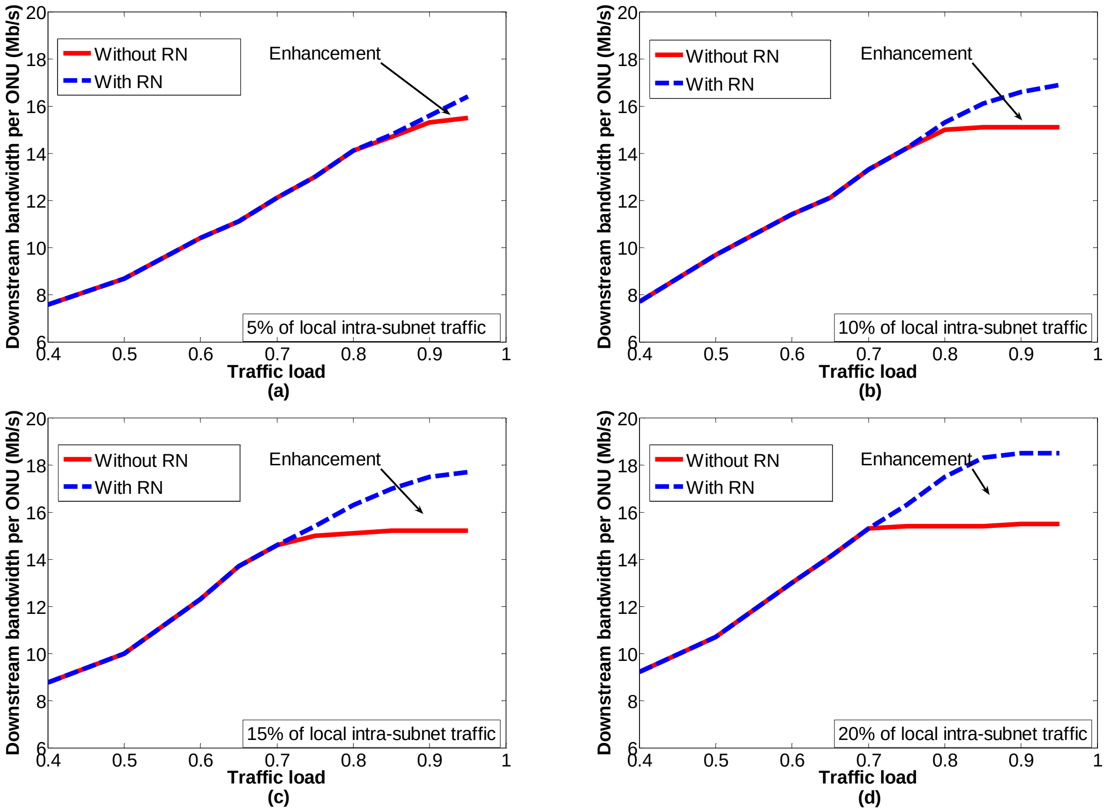

Fig. 5.6: Downstream bandwidth improvement per ONU for different amount of local intra-subnet traffic; where (a), (b), (c) and (d) show improvement for 5%, 10%, 15% and 20% of local intra-subnet traffic respectively.

The downstream bandwidth per ONU of EPON without active RN structure tends to saturate at around 15 Mb/s as this is the limitation of 1 Gb/s total downstream bandwidth (summing up to 15 Mb/s per ONU over 64 ONU gives close to 1Gb/s). However, with active RN in EPON, local intra-subnet traffic will be redirected at the active RN, which creates free time slots at the OLT to accommodate additional external Internet traffic and inter-subnet traffic. This combined downstream traffic from OLT will then be processed at the active RN and merged with previously buffered local intra-subnet traffic to further increase the effective downstream bandwidth per ONU. As a consequence, the total downstream traffic that is received by each ONU in an EPON with active RN will be much greater. This is a synthetic increase in data capacity and the physical downstream and upstream link rates still remain at 1 Gb/s. The downstream bandwidth received by each ONU as shown in Fig. 5.6 can be improved from 7%

to 19% at a traffic load of 0.95 with intra-subnet traffic percentage of 5% to 20% (15.5Mb/s for EPON without active RN compared to 16.5 Mb/s for EPON with active RN at 5% local intra-subnet traffic; and 18.5 Mb/s for EPON with RN at 20% local intra-subnet traffic).

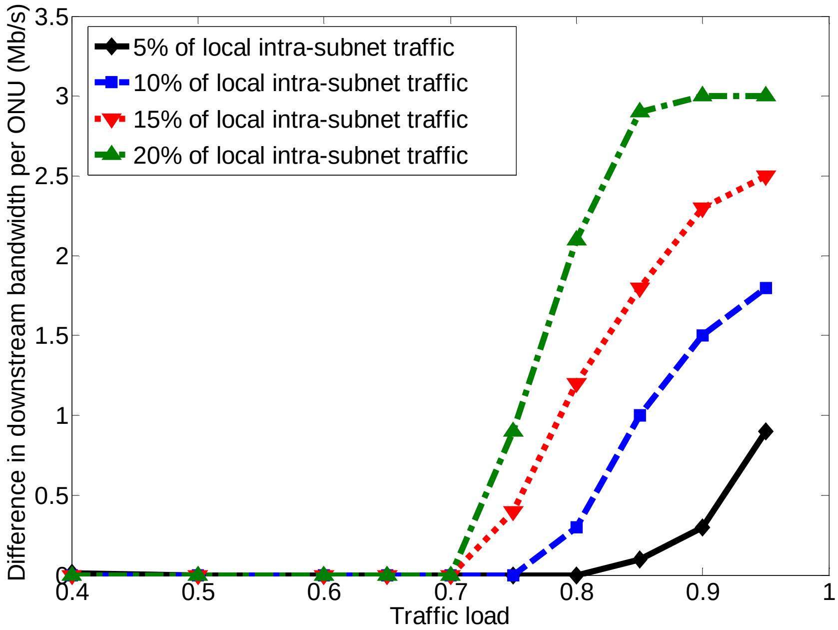

Fig. 5.7: Summary of Fig. 5.6 (a), (b), (c) and (d). Difference in downstream bandwidth per ONU (total of 64 ONUs) shows the total downstream data rate received by each ONU on EPON with RN – downstream data rate received by each ONU without RN.

The summary of downstream bandwidth improvement per ONU on EPON with active RN structure is shown in Fig. 5.7. The figure shows the bandwidth difference, calculated as the difference between the bandwidth allocated for the EPON with active RN and the bandwidth allocated for the EPON without active RN by each ONU at various traffic loads. It is clearly seen that as the traffic load increases, the bandwidth enhancement becomes greater for each ONU. This proves one of the advantages of using the active RN in long reach and high split-ratio EPON in addressing the issue of bandwidth efficiency.

5.5.4. Increasing the number of ONUs for scalability

In this section, fixed downstream external traffic and upstream data rates will be applied to the ONUs as depicted in Fig. 5.3. At traffic load of 0.75 for both downstream and upstream, the following is obtained for EPON without RN (refer to Fig. 5.6 (c)):

(a) ONU upstream data rate: 11.72 Mb/s

(b) OLT downstream data rate: 750 Mb/s

(c) ONU downstream data rate (from internet/external network): 11.72 Mb/s

(d) ONU downstream delay (refer to figure 5 (b)): 20 ms

The simulation is set to have each of the ONUs deliver output upstream traffic of 11.72 Mb/s, which consists of 15% local intra-subnet traffic and 15% inter-subnet traffic. The rest of traffic represents the outgoing traffic to the Internet (or external traffic).

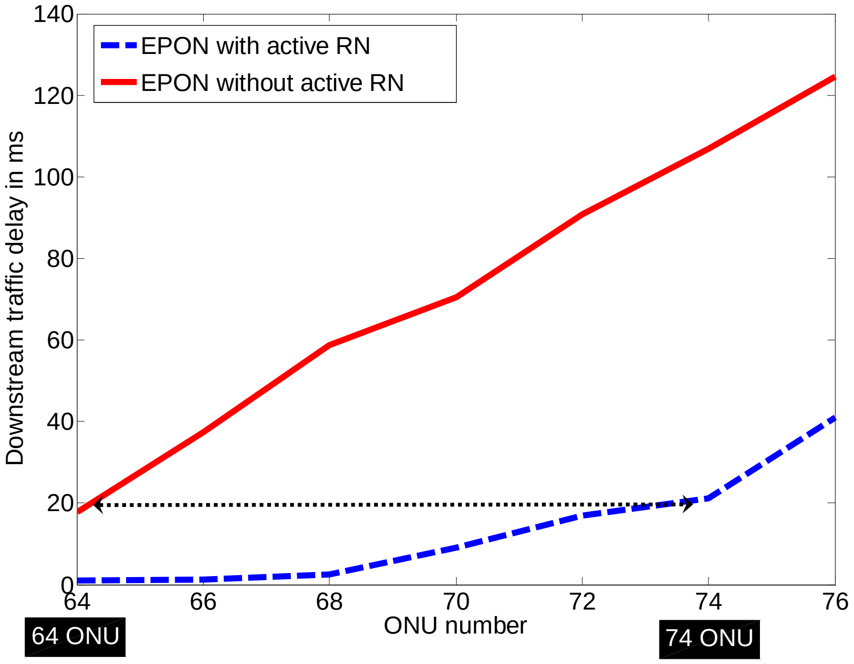

Fig. 5.8: Increase in number of ONUs compared to EPON without active RN structure with having the same upstream, downstream internet data rate.

Having the ONU upstream data rate fixed to be around 11.72 Mb/s, the number of ONUs in both subnets is increased in the simulation by one for each iteration so that the downstream delay reaches 20 ms (Fig. 5.8). Note, this will increase the total ONUs by two for each iteration. With the increase in the number of ONUs, each additional ONU will have the same upstream data rate and downstream received data rate from Internet/external network (Note that this traffic excludes the local inter-subnet traffic). Consequently, the values of OLT downstream data rate will change as the additional ONUs will require additional downstream bandwidth. Fig. 5.8 shows the increase in downstream delay while the number of ONUs in the EPON with active RN is increasing. At the case where the number of ONUs increases to 10 (which is 74 ONUs), the downstream delay reaches 20 ms, which is the same as the 64 ONUs case for EPON without active RN. In general, Fig. 5.8 tells us that with the use of active RN in EPON, the EPON is capable of supporting more ONUs in the network while experiencing similar quality of service (QoS) in terms of downstream traffic delay and downstream data rate from external network.

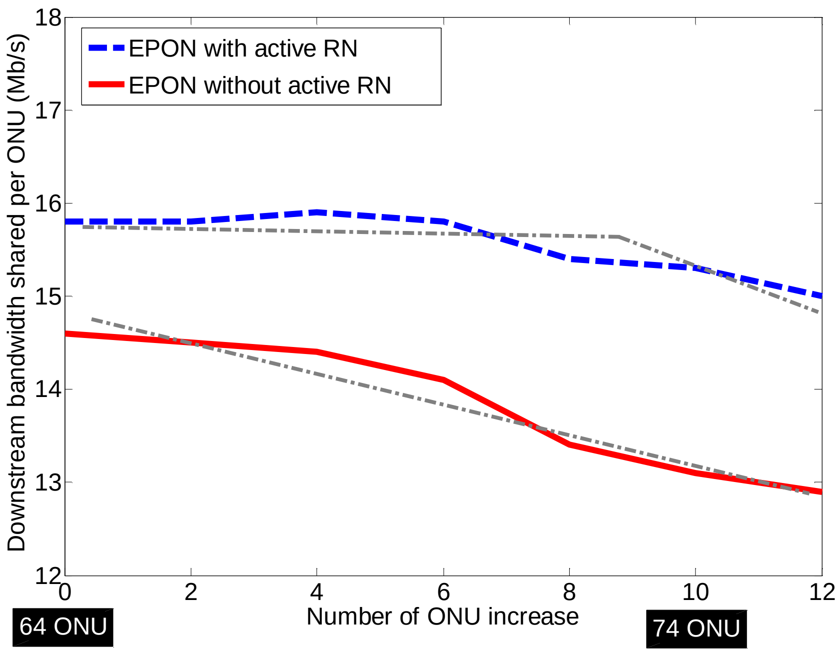

Fig. 5.9: Downstream data rate received per ONU (for a total of 64 ONUs), where the dotted-dash grey lines represent the theoretical estimation described in the next section.

To further analyse the results, Fig. 5.9 and Fig. 5.10 show the ONU processed downstream bandwidth and the total downstream bandwidth processed by the entire N ONUs as N increases from 64 ONUs to 76 ONUs (assuming downstream traffic delay of 20 ms). Fig. 5.9 shows that almost equal amount of downstream bandwidth for each ONU if active RN is used in the network until N reaches around 74 as this is the cut-off point where the feeder fibre's 1 Gb/s capacity is reached. Hence the value of downstream data rate received by each ONU beyond 74 ONUs will drop. However, for the case of EPON without active RN, the downstream data rate received per ONU is decreasing with each additional ONU. This is due to the reason that the increasing number of ONUs in the network will further increase the total upstream traffic results in additional local intra and inter-subnet traffic. However, the downstream link rate for EPON without active RN is limited to 1 Gb/s. Therefore, the downstream bandwidth per ONU is reduced with the increase number of ONUs. For EPON with active RN case, the local intra-subnet traffic will be redirected at the active RN instead of OLT. This function causes the OLT to have more timeslots to transmit increasing downstream traffic due to the increase in ONU number. As a result, the ONU received downstream bandwidth will increase. The advantage of the whole process can be seen in Fig. 5.10 as the total downstream bandwidth received by all *N* ONUs will increase as the value of *N* increases. However, for EPON without active RN, total downstream processed bandwidth will be saturated closed to 1 Gb/s since this is the limitation for EPON without active RN.

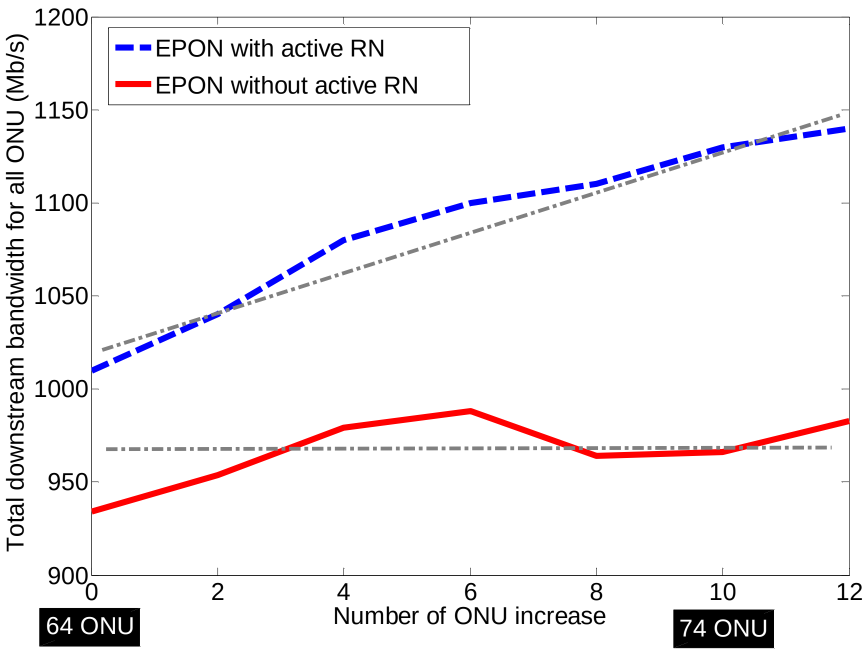

Fig. 5.10: Total downstream data rate received by all ONU (sum of *n* ONU downstream data rate), where the grey dotted-dash lines represent the theoretical estimation described in the next section.

5.6. Theoretical Analysis

In this section, theoretical estimations are divided into two sub-sections; first one presents the downstream bandwidth improvement and the second sub-section discusses the increase of ONU number using active forwarding RN in EPON. Table 5.2 describes the definitions of various parameters, which will be used in this section.

PARAMETERS	DEFINITION
N	Number of ONUs
$C_{capacity}$	Link capacity (Mb/s)
α	Local traffic percentage (%)
$L_{traffic}$	Traffic load (0.1 – 0.9)
T_{ds}	Total downstream traffic at OLT (Mb/s)

Table 5.2: Definition of parameters for theoretical analysis on improving performances in large scale EPON using active RN.

5.6.1. Improvement of downstream data rate per ONU

The link capacity of an EPON system is set to be 1 Gb/s, $C_{capacity}$ = 1 Gb/s and the number of ONU, N is set as 64 to be identical to simulation setup discussed in section 5.4. According to the simulation setup, the local intra-subnet traffic, α has the value varied from 5% to 20% of $L_{traffic}$ since $L_{traffic}$ will represent the traffic load (varied from 0.4 to 0.95 since similar performance will be achieved at low traffic load between EPON with and without active RN) for both upstream and downstream. The total traffic that is needed to be redirected at the OLT is 2 times α for EPON without active RN since both the local intra-subnet and inter-subnet traffic will route through the OLT. However, for EPON with active RN, the total local traffic that is required to go through OLT is α since local intra-subnet traffic will be routed through the active RN as shown below:

$$\gamma = \begin{cases} \alpha \times L_{traffic} \times C_{capacity} & \text{for EPON with active RN} \\ 2\alpha \times L_{traffic} \times C_{capacity} & \text{for EPON without active RN} \end{cases}. \quad (5.1)$$

Hence the total amount of traffic that is needed to be transmitted downstream from the OLT is, T_{ds} = $\min\begin{cases}\gamma+\left(L_{traffic}\times C_{capacity}\right)\\ 1000\end{cases}$ Mb/s. Note that at high traffic load and large amount of local traffic needed to be redirected at the OLT, necessary frames will be buffered due to the EPON link capacity limit of 1 Gb/s. Without active forwarding in conventional EPON, the local traffic will be mixed with the external Internet traffic at the OLT. Therefore the estimated downstream data rate available per ONU can be calculated as:

$$BW_{ds\_withoutRN}=\frac{T_{ds}}{N}, \tag{5.2}$$

depending on different traffic load, $L_{traffic}$.

However, if active RN is in place to redirect local intra-subnet traffic, the estimated downstream data rate available per ONU is assumed to be:

$$BW_{ds\_withRN}=\frac{T_{ds}+\beta}{N}, \tag{5.3}$$

where T_{ds} term represents the downstream traffic sequence from the OLT (external traffic + inter-subnet traffic as refer to equation (5.1)) while the β represents the amount of buffered local intra-subnet traffic in the active RN that can be calculated as β = (α × Ltraffic × Ccapacity). Hence, equations (5.2) and (5.3) are drawn with α value of (5%, 10%, 15% and 20%) and $L_{traffic}$ value of (0.4 to 0.95).

The theoretical estimation curves of four different local traffic percentage scenarios, α = {5%, 10%, 15%, 20%} for evaluation of downstream data rate per ONU in EPON with and without active RN are shown in Fig. 5.11. As a comparison to Fig. 5.6, they both show similar curves. Fig. 5.11 (b), (c) and (d) show a cut-off in downstream data rate at 15.625 Mb/s due to the link capacity of EPON without active RN of 1 Gb/s. However, for EPON incorporating active RN system, only local inter-subnet traffic is required to be redirected at the OLT. Local intra-subnet traffic will be redirected at the active RN causing the data rate of each ONU to increase. Fig. 5.11 shows the downstream received data rate for each ONU can be improved from 5% to 19% at a traffic load of 0.95 with local intra-subnet traffic percentage of 5% to 20% (15.63Mb/s for EPON without RN compared to 16.33 Mb/s for EPON with RN at 5% local intra-subnet traffic; and 18.60 Mb/s for EPON with RN at 20% local intra-subnet traffic), which is very consistent with simulation results demonstrated in Fig. 5.6.

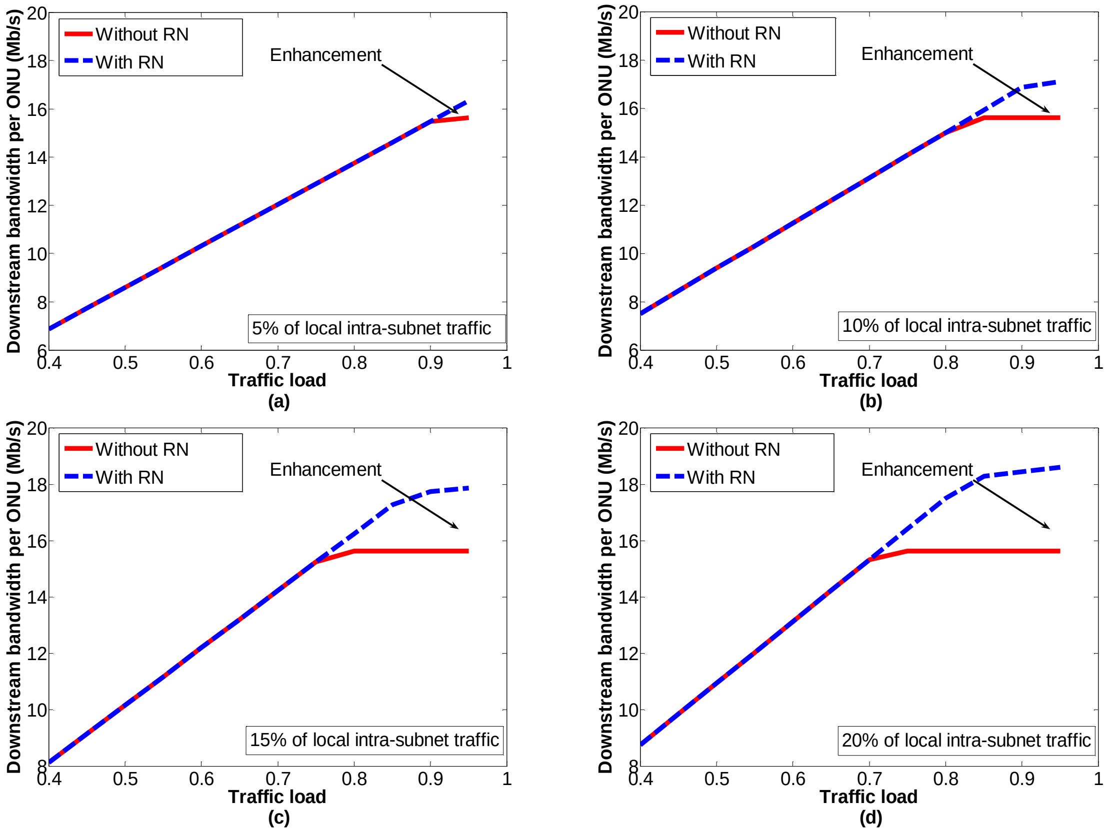

Fig. 5.11: Theoretical estimation on downstream bandwidth improvement per ONU for different amount of local intra-subnet traffic; where (a), (b), (c) and (d) show improvement for 5%, 10%, 15% and 20% of local intra-subnet traffic respectively.

The summary of downstream bandwidth improvement per ONU on EPON with RN structure is shown in Fig. 5.12. To be consistent with the simulation results, the figure shows the bandwidth difference, calculated as the difference between the bandwidth allocated for the EPON with RN and the bandwidth allocated for the EPON without RN by each ONU at various traffic loads. Similar to Fig. 5.7, it is clearly seen that as the traffic load increases, the bandwidth enhancement becomes greater for each ONU. At the highest traffic load of 0.95, Fig. 5.12 shows the estimated improved downstream data rate received by each ONU using active RN to be 0.70 Mb/s, 1.48 Mb/s, 2.22 Mb/s and 2.97 Mb/s for local traffic percentage of 5%, 10%, 15% and 20%. In the other hand, the simulation results of Fig. 5.7 give similar value of 0.90 Mb/s, 1.80 Mb/s, 2.50 Mb/s and 3.00 Mb/s. These small differences are due to the infinitive variance of Pareto distribution in the self-similar traffic generation [26]. This infinitive variance causes the aggregated load to fluctuate considerably. Therefore, the generated traffic that is used in the simulation will not produce an exact value for the traffic load. The generated traffic sequence will result in a maximum of ±50 Mb/s difference in traffic load setting.

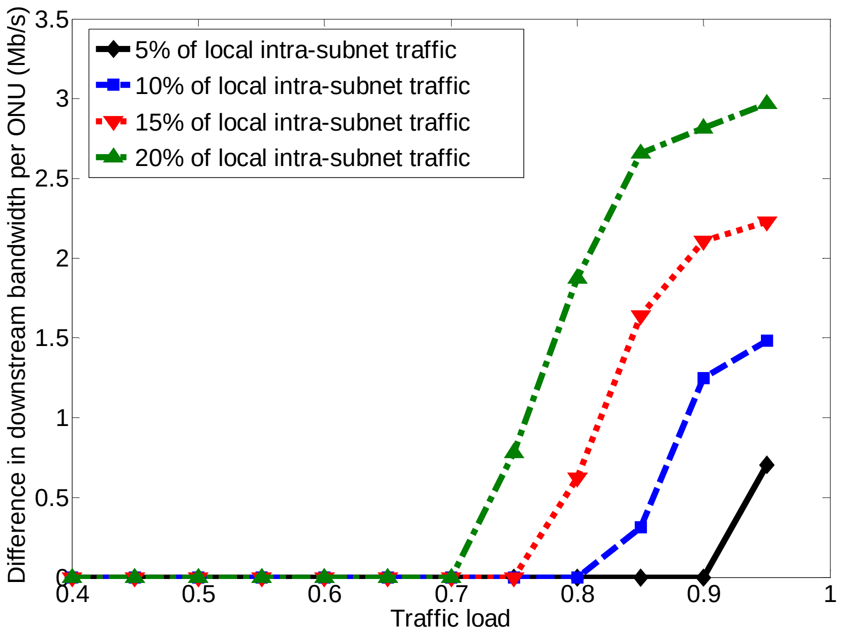

Fig. 5.12: Theoretical estimation on the downstream data rate per ONU improvement using active RN (mean downstream data rate per ONU of without RN – mean downstream data rate per ONU with RN).

5.6.2. Improvement in ONU number scalability

In section 5.5.4, the simulation results showed that each ONU will generate the upstream bandwidth of equal to 64 ONU. Among the traffic sequence generated by each ONU, a percentage of 15% will be assumed as local intra-subnet traffic while another equal amount will be assigned as local inter-subnet traffic. For the EPON without active forwarding RN structure, both local intra-subnet and local inter-subnet traffic are required to be buffered and redirected at the OLT. However, for EPON with active RN, the local intra-subnet traffic will be redirected at the active RN. Refer to Table 5.2, it is assumed in this section that N = {64, 66, 68, 70, 72, 74, 76, 78}, $C_{capacity}$ staying 1 Gb/s, $\alpha = 0.15$ (15% of local intra-subnet and inter-subnet traffic amount), and $L_{traffic}$ = 0.75 for each ONU, which means the upstream bandwidth per ONU is fixed at, $BW_{ONU} = 0.75 \times C_{capcity}/64$, which is equal to 11.72 Mb/s. The total local traffic that is required to be redirected at the OLT for with and without active RN as defined in equation (5.1) will be changed to include N:

$$\gamma = \begin{cases} \alpha \times N \times BW_{ONU} & \text{for EPON with active RN} \\ 2\alpha \times N \times BW_{ONU} & \text{for EPON without active RN} \end{cases} \tag{5.4}$$

Hence the total amount of traffic that is needed to be transmitted downstream from the OLT is, $T_{ds} = \min \begin{cases} N \times BW_{ONU} + \gamma \\ 1000 \end{cases}$ Mb/s. As the number of ONU, N increases, larger amount of local traffic needed to be redirected at the OLT (since all ONU will be given the same bandwidth as in 64 ONU EPON), necessary frames will be buffered due to the EPON link capacity limit of 1 Gb/s. Without active forwarding in conventional EPON, the local traffic will be mixed with the external traffic at the OLT. Therefore the estimated downstream data rate available per ONU can be calculated similar to equation (5.2) but depending on different value of N.

However, if the active RN is in place to redirect local intra-subnet traffic, the estimated downstream data rate available per ONU is assumed to be:

$$BW_{ds\_withRN} = \frac{T_{ds} + \beta}{N}, \tag{5.5}$$

where T_{ds} term represents the downstream traffic sequence from the OLT (external traffic + inter-subnet traffic) while the β represents the amount of buffered local intra-subnet traffic in the active RN that can be calculated as $\beta = (\alpha \times N \times BW_{ONU})$. Hence, equations (5.2) and (5.5) are drawn with N value of (64, 66, 68, 70, 72, 74, 76, 78).

To be consistent with simulation results in Fig. 5.9, Fig. 5.13 shows the theoretical estimation of downstream data rate received for each ONU against different number of ONU (from 64 to 78) in the EPON system. For EPON without active RN, the received downstream data rate decreases when the network is needed to support more ONU. This is due to the reason that 1 Gb/s EPON link capacity is easily reached at high traffic load when the number of ONU increases. Although for EPON with active RN is also dependent to 1 Gb/s link capacity, this limit will only be reached at the point where ONU number is increased to 74 according to Fig. 5.13. This is mainly due to the reason that significant amount of local intra-subnet traffic has been redirected at the active RN to allow the OLT to accommodate more external downstream traffic. Furthermore, with the increase of ONU number, the amount of local intra-subnet traffic also increases, which further increase the downstream data rate received by each ONU in the network. Fig. 5.13 suggests a similar performance curve compared to the simulation results in Fig. 5.9, which also proves the feasibility of the network simulation carried out in this chapter.

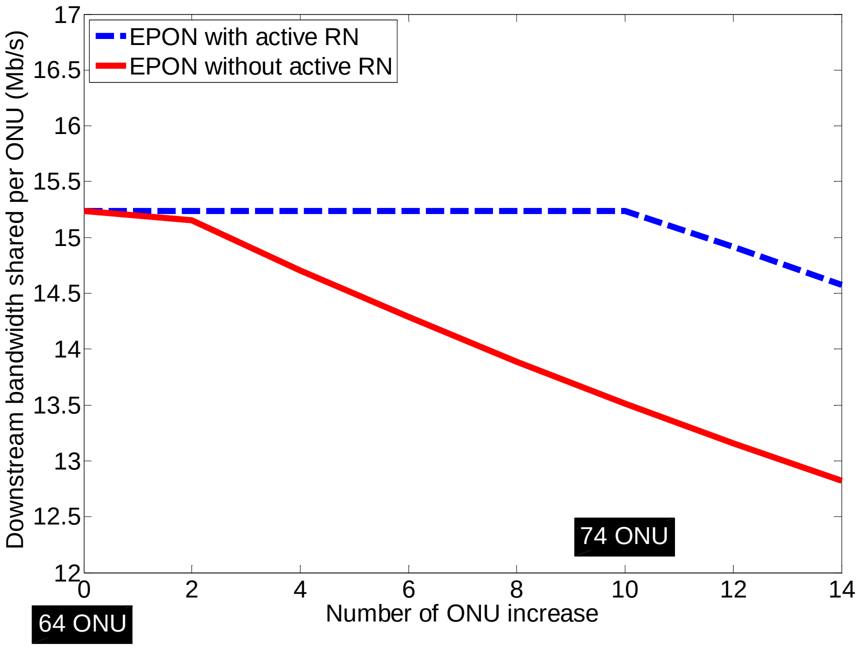

Fig. 5.13: Theoretical estimation on the downstream data rate received per ONU (this result is shown in Fig. 5.9 as a comparison).

Another representation of the scalability advantage of using active forwarding RN in large scale EPON is shown in Fig. 5.14. As a comparison to simulation results in Fig. 5.10, both figures show the same result that the total downstream data rate for conventional EPON without RN can not exceed 1 Gb/s as this is the link capacity limitation. However, for EPON with active RN structure, the summation of the data rate received by all ONU can breakthrough the EPON limitation of 1 Gb/s until the ONU number is increased to 74 where the saturation will begin. This is due to the reason that only local inter-subnet traffic needs to go through the OLT while the local intra-subnet traffic are redirected at the active RN. The combined local inter-subnet and external downstream traffic (which will not trigger the 1 Gb/s link limit due to the absent of local intra-subnet traffic) will go through the feeder link and arrive at the active RN to combine with previously buffered local intra-subnet traffic.

Therefore, the actual throughput of the system can exceed the limit of 1 Gb/s, which also proves that by using active forwarding RN in EPON, the amount of ONU in the network can be increased while supporting the same data rate for each ONU as compared to 64 ONU in conventional EPON without active RN. As a result, both Fig. 5.13 and 5.14 show similar curves as compared to Fig. 5.9 and 5.10. As the number of ONU increases, the actual downstream data rate received by each ONU can be maintained the same if active RN is used in the network; however this is impossible to be achieved for conventional EPON. Also, these results verify the feasibility scheme and validity of the simulation results since the theoretical estimations give similar results.

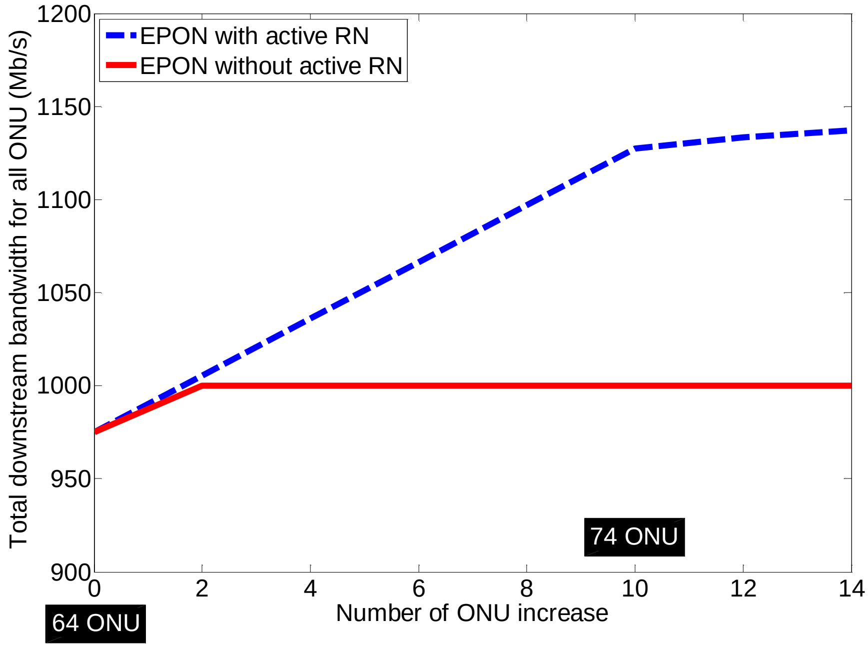

Fig. 5.14: Theoretical estimation on the total downstream data rate received for all ONU (this result is shown in Fig. 5.10 as a comparison).

5.7. Conclusion

In the previous chapter, the simple hybrid active EPON scheme with the implementation of repeater based active forwarding RN has been presented to improve the network performance such as local traffic and external downstream traffic delays. This chapter presents the use of such a scheme in high split-ratio and long reach EPON system with the aim to address the downstream bandwidth bottleneck and scalability issues in access network. Scalability of the active RN has been tested to prove that same packet delay characteristics and buffer size are achieved for increased network size so that the similar efficiency in using the active RN can apply regardless of the network size.

In section 5.5.3, the major advantage of the scheme on solving bandwidth bottleneck on long reach and high split-ratio EPON has been demonstrated. Simulation results show large enhancement in downstream data rate received per ONU of up to 19% (or 3 Mb/s per ONU for EPON with 64 ONUs) can be achieved by using active forwarding RN in EPON. Besides, the other major benefit of the scheme on solving scalability issue has been explained in section 5.5.4. Under the conditions of the same downstream traffic delay, external downstream and upstream data rate by each ONU; EPON with active RN can accommodate 74 ONUs compared to only 64 ONUs by EPON without active RN. This is a nearly 16% increase in total ONU number that can be supported by the network.

In section 5.6, theoretical analysis on the two major simulation analyses has been developed. Theoretical results show similar performance curves compared to simulation results to prove the feasibility of the scheme as well as the accuracy of the network simulation model. In summary, low cost active RN with MAC forwarding scheme can be used to increase the downstream data rate or the number of customers in an EPON system without any modification to the underlying protocols. This leads to a network with longer reach and greater sharing of cost between a larger customer base.

5.8. References

[1] T. Anderson, "PONs offer higher speeds, lower price per megabit," [Online]. Available: http://lw.pennnet.com/display_article/320162/13/ARTCL/none/none/1/PONs-offer-higher-speeds,-lower-price-per-megabit/

[2] K. Grobe, and J-P. Elbers, "PON in adolescence: from TDMA to WDM-PON," *IEEE Commun. Mag*. vol. 46, no. 1, pp. 26-34, Jan 2008.

[3] G. Kramer, G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," *IEEE Commun. Mag.* Vol 40, no. 2, pp. 66-73, Feb. 2002.

[4] I. Cale, A. Salihovic, M. Ivekovic, "Gigabit Passive Optical Network – GPON," in *Proc. 29th International Conference on Information Technology Interfaces*, pp. 679-684, Jun. 2007.

[5] H. Roberts, M. Rude, J. Solum, "Cost Effective High Split Ratios for EPON," presented at the *IEEE 802.3 Ethernet in the first mile study group*, July 2001.

[6] P. D. Townsend, G. Talli, E. K. MacHale, C. Antony, "Long Reach PONs," in *Proc. The 7th International Conference on Optical Internet*, pp. 1-2, Oct. 2008.

[7] I. Van de Voorde, C. M. Martin, J. Vandewege, and X. Z. Qiu, "The SuperPON Demonstrator: An Exploration of Possible Evolution Paths for Optical Access Networks," *IEEE Commun. Mag*. Vol. 38, no. 2, pp. 74-82, Feb. 2000.

[8] X. Z. Qiu, Y. C. Yi, P. Ossieur, S. Verschuere, D. Verhulst, B. De Mulder, W. Chen, J. Bauwelinck, T. De Ridder, B. Baekelandt, C. Melange, J. Vandewege, "High performance burst-mode upstream transmission for next generation PONs," in *Proc. Asia Optical Fiber Communication and Optoelectronics Conference*, pp. 1-3, 24-27 October 2006.

[9] D. Nesset, R. P. Davey, D. Shea, P. Kirkpatrick, S. Q. Shang, M. Lobel, B. Christensen, "10 Gb/s bidirectional transmission in 1024-way split, 110 km reach, PON system using commercial transceiver modules, super FEC and EDC," in *Proc. 31st European Conference on Optical Communication*, pp. 135-138, 2005.

[10] I. Van de Voorde, C. Martin, H. Slabbinck, L. Gouwy, B. Stubbe, X. Z. Qiu, J. Vandewege, P. Solina, "Evaluation of the super PON lab-demonstrator," in *Proc. 11th International Conference on Integrated Optics and Optical Fibre Communications and 23rd European Conference on Optical Communications*, vol. 3, pp. 331-334, Sept. 1997.

[11] D. B. Payne and R. P. Davey, "The Future of Fiber Access Systems," *J. BT Tech*. Vol. 20, pp. 104-14, 2002.

[12] G. Talli, C. W. Chow, P. Townsend, R. Davey, T. De Ridder, X. Qiu, P. Ossieur, H. Krimmel, D. Smith, I. Lealman, A. Poustie, S. Randel, H. Rohde., "Integrated Metro and Access Network: PIEMAN," in *Proc. 12th European Conference Networks and Optical Communication*, pp. 493-500, 2007.

[13] G. Talli and P. D. Townsend, "Feasibility Demonstrator of 100 km long reach DWDM SuperPON with Upstream Bit Rates of 2.5 Gb/s and 10 Gb/s," in *Proc. Optical Fiber Communication Conference*, OSA Technical Digest Series, paper OFI1, 2005.

[14] D. P. Shea, and J. E. Mitchell, “Long Reach Optical Access Technologies,” *IEEE Networks Mag*. vol. 21, no. 5, pp. 5-11, Sept. 2007.

[15] A. V. Tran, C. J. Chae, and R. S. Tucker, “Low-Cost Optical Access System using Repeater, VCSEL Transmitters and Multi-mode Fibers”, in *Proc. 32nd European Conference on Optical Communication*, pp. 135-138, 2006.

[16] A. V. Tran, C.-J. Chae, R. S. Tucker, “Low-cost and scalable passive optical network architecture using remote repeater,” *IEE Electron*. *Lett*. vol. 42, no. 10, pp. 589-591, May 2006.

[17] A. V. Tran, C.-J. Chae, R. S. Tucker, “Cascadability performance of remote-repeater-based FTTP systems,” *IEE Electron*. *Lett*. vol. 42, no. 24, pp. 1418-1420, Nov. 2006.

[18] S. Vanhastel, R. Hernandez, “Enabling IPTV: What’s Needed in the Access Network,” *IEEE Commun. Mag.* Vol 46, no. 2, pp. 94-100, Feb. 2008.

[19] T. Wauters, K. Vlaeminck, W. V. Meerssche, F. D. Turck, B. Dhoedt, P. Demeester, S. V. Berghe, E. Six, T. V. Caenegem, “IPTV Deployment – Trigger for Advanced Network Services!,” *The J. The Commun. Network*, vol. 5, no. 3, pp. 63-69, Jul. 2006.

[20] Siemens and Juniper Networks, “High Quality and Resilient IPTV Multicast Architecture – An Overview of RESIP Multicast Architecture Design Guidelines,” *Siemens Communications and Juniper Networks Inc. White Papers*, 2006.

[21] C. A. Chan, M. Attygalle, A. Nirmalathas, “Active Remote Node with Layer Two Forwarding for Improving Performance of EPON”, in *Proc. IEEE Conference on Global Telecommunications*, pp. 1-5, 2008.

[22] G. Kramer, “Ethernet Passive Optical Networks,” *McGraw-Hill Prof*., 2004, ISBN:0071445625.

[23] G. Kramer, B. Mukherjee, G. Pesavento, “IPACT a dynamic protocol for an Ethernet PON (EPON),” *IEEE Comm*. *Mag*. vol. 40, no. 2, pp. 74-80, Feb 2002.

[24] J. Wang, L. Sun, X. Jiang, Z. Wu., “IGMP snooping: a VLAN-based multicast protocol,” *in Proc. 5th IEEE International Conference on High Speed Networks and Multimedia Communications*, pp. 335 – 340, 2002.

[25] M. S. Taqqu, W. Willinger, R. Sherman, “Proof of a fundamental result in self-similar traffic modelling,” *ACM/SIGCOMM Comp. Comm. Rev*. vol. 27, pp. 5-23, 1997.

[26] S. N. Subramanian, L.-N. Tho, “Traffic modelling in a multi-media environment,” in *Proc. Canadian Conference on Electrical and Computer Engineering*, vol. 2, pp. 838-841, Sep. 1995.

6 Active RN for Improving Upstream Performance in EPON

6.1. Introduction

In the previous chapters, we have demonstrated that the Ethernet passive optical network (EPON) can be improved by incorporating an active remote repeater node (RN) to achieve extended reach and larger split-ratio in order to support a large number of customers. Furthermore, active forwarding scheme implemented in the active RN to perform local traffic redirecting was demonstrated through simulation, which is able to improve several network parameters such as local and external traffic delay and the downstream bandwidth. However, these performance enhancements are focused on downstream improvements, and upstream performance with the use of the active RN in EPON has not been evaluated.

As discussed in Chapter 2, broadcast downstream transmission from OLT to ONUs is used in EPON where Ethernet frames are broadcasted to all ONUs and the ONUs will retain the desired frames based on the physical logical link identity (LLID) address encapsulated in the EPON frame [1-3]. However in the upstream transmission, time division multiple access (TDMA) technique is used to avoid collision at the passive combiner. A specific timeslot will be allocated to each ONU by the OLT and the particular ONU will transmit packets during the timeslot assigned. To evaluate the downstream performance of using the active RN in the previous chapters (Chapters 4 and 5), static or fixed bandwidth assignment is used since the benefits of using the active RN become significant at high traffic load, where static bandwidth assignment (SBA) technique produces similar upstream performance compared to the dynamic bandwidth assignment (DBA) technique [4]. Nevertheless, the benefits of using the active RN should not be limited to downstream transmission; it can be extended to improve the upstream performance of EPON by developing a specific DBA mechanism that is suitable for the active forwarding network architecture.

In this chapter a novel local traffic prediction-based DBA mechanism (LT-DBA) incorporated with remote repeater based EPON with active forwarding will be presented. The LT-DBA aims to improve the bandwidth utilisation, average packet delay, average packet loss ratio and average queue size performances of EPON in upstream transmission in comparison to conventional bandwidth assignment techniques such as fixed-service and interleaved polling algorithm with adaptive cycle time (IPACT) to provide a more efficient EPON system. The rest of the chapter is organised as follows: Section 6.2 discusses the motivation of using the active forwarding RN to improve the upstream transmission performance in EPON system. Section 6.3 gives a detail explanation on LT-DBA including the idea of excess timeslot granting and collision avoidance techniques for LT-DBA. Section 6.4 demonstrates the simulation setup of LT-DBA used in EPON with active forwarding RN. Section 6.5 presents the simulation results in four parts. Average packet delay and average queue size are discussed in sections 6.5.1 and 6.5.2 while section 6.5.3 and section 6.5.4 demonstrate the improvements in average frame loss rate and average upstream bandwidth per ONU. Finally section 6.6 summarises the overall chapter.

6.2. Improving Upstream Performance Using Active RN

Recall the major functions of an active forwarding RN in EPON are to filter unwanted frames with destination to the other subnets and redirect local intra-subnet traffic. In order to perform these operations, the active RN listens to all the incoming frames' header information (both upstream and downstream) and form the forwarding table to identify the medium access control (MAC) and LLID of ONUs in each subnet that allows the active RN to filter and forward network traffic appropriately [4]. When the upstream frames are received at the active RN, the frames will be buffered to process the header reading to determine the destination of the frame to be either redirected back to own subnet or transmitted upstream to the OLT. After the forwarding decision has been made, the frame will be either redirected back to the subnet in downstream transmission (if the frame is destined to an ONU within the subnet) or transmitted upstream to OLT if it belongs to external or Internet traffic. In the downstream direction, the active RN will make the decision to either transmit the particular frame downstream or discard the frame if the destination of the frame is not within the subnet connected to the active RN to create empty timeslots, which are used to fill in the previously buffered local intra-subnet frames. This was shown to improve the downstream bandwidth and traffic latency. However in the upstream direction, empty timeslots occur due to local intra-subnet frames redirection, which reduces the utilisation and efficiency of the transmission link.

The graphical explanation of the upstream performance without DBA for active RN in EPON architecture as discussed in Chapters 4 and 5 is shown in Fig. 6.1. For simplicity, only four ONUs are displayed in the figure. Specific timeslots have been allocated to all four ONUs based on the requests from these ONUs; while if SBA or fixed service is used, all four timeslots will have equal size. Since ONU 3 is communicating with ONU 1, this frame will be buffered at the active RN pending for downstream transmission. Therefore, this time interval that is previously assigned for ONU 3 in the upstream transmission will be left empty by the active RN. After the final passive combination, the upstream traffic sequence with empty timeslots will arrive at the OLT. Although the current EPON with active RN structure can improve the downstream transmission performances, the upstream utilisation is inefficient as many empty timeslots will occur in the upstream transmission sequence as the amounts of traffic load and local intra-subnet traffic increase. Therefore, intelligent bandwidth assignment model can be implemented to utilise these empty timeslots due to local intra-subnet redirection at the active RN.

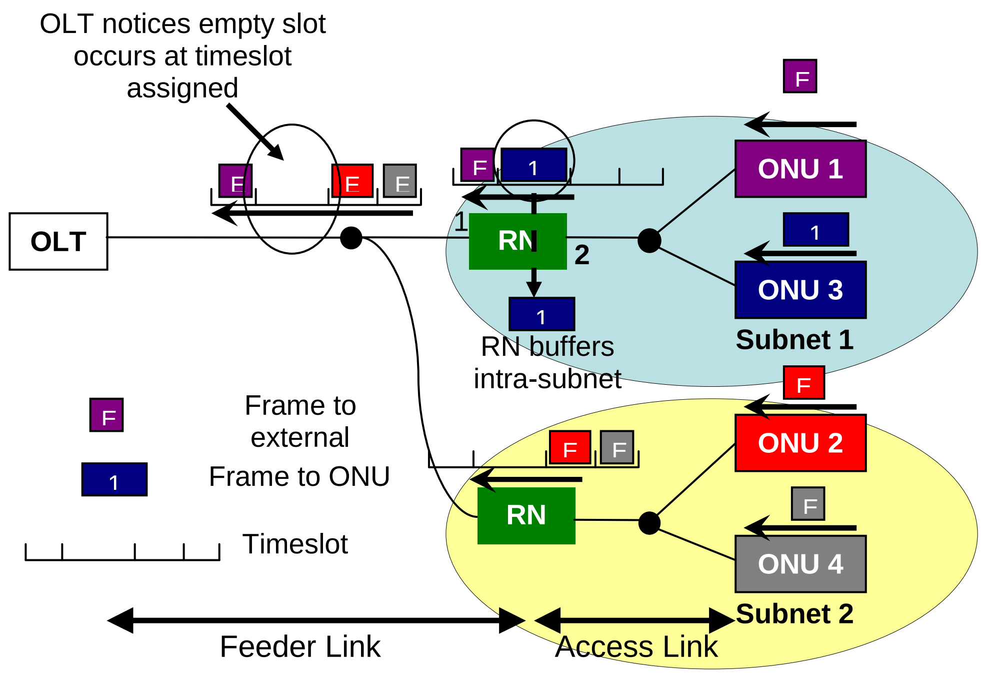

Fig. 6.1: EPON with active RN architecture showing empty timeslots occur in upstream transmission due to local intra-subnet traffic redirection.

The OLT detects empty timeslot, which is due to local intra-subnet redirection and assumes that the inter-ONU communication will exist for a considered period of time. The OLT will then allow excess granting of timeslots to ONU 3 in the next transmission cycle as shown in Fig. 6.2. Following the buffering of local intra-subnet frame at the active RN, the frames that are sent during the excess granting time interval will be scheduled to fit in the empty timeslot (the RN upstream scheduler will be discussed in section 6.3.2). As the ONU is allowed to transmit more frames upstream than it is possible in standard DBA method, this will increase the utilisation of the upstream transmission. However, such mechanism requires the OLT to have the knowledge on realising the existence of local intra-subnet traffic redirection function at the active RN and collision avoidance since the ONUs are allowed to send more frames on time intervals that belong to the other ONUs in other subnets. Furthermore, the active RN requires an upgrade on upstream transmission to include a scheduler machine to guarantee fair and efficient EPON system. In the following section, the proposed LT-DBA method is discussed in detail.

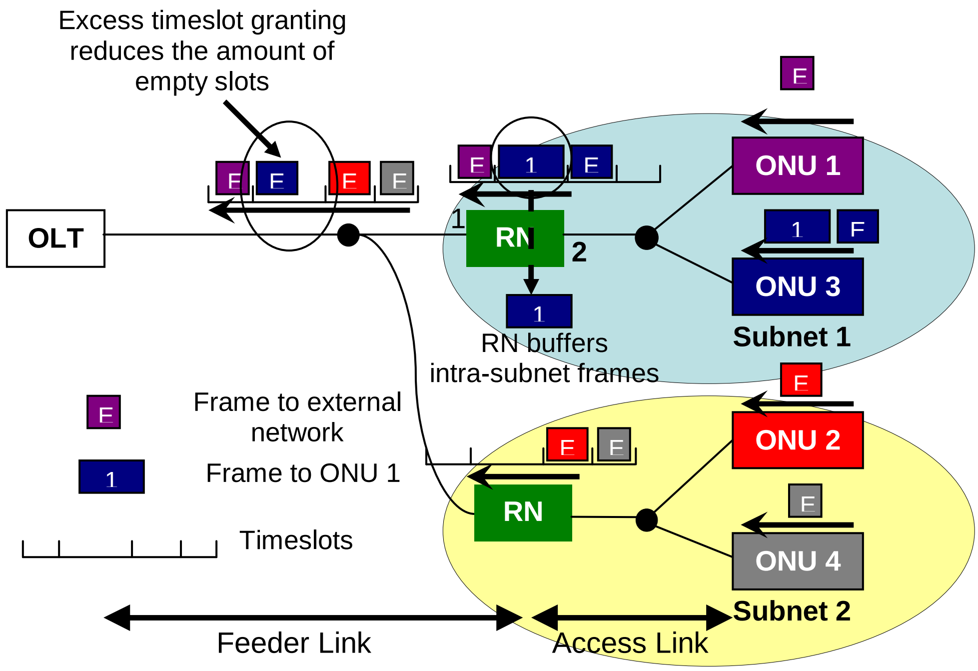

Fig. 6.2: EPON with active RN architecture showing the excess granting of timeslots for preventing empty slots occurring at OLT receiver to improve upstream utilisation.

6.3. Local Traffic Prediction-based DBA (LT-DBA)

According to IEEE 802.3ah standard, DBA mechanism is opened for the vendors to customise as a way of differentiating their products in the market. Among the various DBA algorithms discussed in Chapter 2 [4-8], IPACT appears to be the foundation of most DBA algorithms. In this scheme, the OLT keeps the information of each ONU's buffer size, round-trip time (RTT) in a polling table [4]. The OLT will decide the size of upstream transmission for an ONU based on polling approach before the transmission from previous ONU has arrived [4]. The proposed LT-DBA algorithm, which consists of two phases, is built on top of the interleaved polling approach (which is named the 'standard DBA algorithm'). In the first phase of LT-DBA, the OLT will run the standard DBA algorithm to allocate timeslots to corresponding ONUs. Consequently, the LT-DBA algorithm will make the decision to excess granting the particular ONU's assigned timeslots based on its previous upstream transmission in the second phase. The excess granting of timeslots in LT-DBA is designed to work in conjunction with active RN with layer two forwarding scheme in EPON. Since the downstream performances have been dramatically improved with the use of active RN, the LT-DBA mechanism is designed augment the forwarding at the active RN and to increase the upstream utilisation and reduce the packet delay and packet loss ratio.

Most of the DBA algorithms can be generalised as dynamic distributed realisations with weighted round-robin scheduler [6]. The OLT will assign a certain amount of bandwidth to each ONU based on the requested slot-size amount stated on the REPORT message generated from the ONU [3]. The proposed LT-DBA algorithm will use the 'limited service' DBA as the fundamental of the mechanism [2]. In this algorithm, the slot-size prior to excess granting for ONU i on cycle k, $G\_DBA_{i,k}$ is assigned by the OLT based on the formula:

$$G\_DBA_{i,k} = \min \begin{cases} v_{i,k} \\ G^{\max} \end{cases} \quad (6.1)$$

where $v_{i,k}$ represents the requested slot-size by ONU i for transmission cycle k and G^{max} represents the maximum slot-size that can be assigned for each ONU. This formula will be used in the DBA machine to determine the total slot-size available for ONU i as listed in Fig. 6.3, which represents the pseudo-code of the proposed LT-DBA mechanism.

Define $G_{i,k}$ = Granted slots on cycle k for ONU i;
Define $R_{i,k}$ = Received slots on cycle k for ONU i;
Calculate empty slots from cycle k: $L_{i,k} = G_{i,k} - R_{i,k}$;
Received *REPORT_i;*
Run *DBA algorithm* (e.q. (6.1)) to obtain $G\_DBA_{i,k+1}$;

NOTE: Excess grant (LT-DBA) is activated once the normal DBA granted slot is the maximum
if $G\_DBA_{i,k+1} = G^{max}$

Case 1: free slots occur on previously assigned upstream slots from ONU *i*; grant extra slots for this cycle
{if $L_{i,k} > L_{threshold}$;
{$G_{i,k+1} = G\_DBA_{i,k+1} + L_{i,k}$ }

Case 2: **no** free slots occur on previously assigned upstream slots from ONU *i*, no extra slots will be granted for this cycle
else if $L_{i,k} < L_{threshold}$ & $L_{i,k} \neq 0$
{$G_{i,k+1} = G\_DBA_{i,k+1}$}
end}
else
{$G_{i,k+1} = G\_DBA_{i,k+1}$}
end

Fig. 6.3: Pseudocode for the proposed LT-DBA algorithm that is implemented at the OLT.

As stated in Fig. 6.3, following the receipt of REPORT message from ONU *i*, the DBA machine at the OLT will determine the normal slot-size that will be granted to ONU *i* for the transmission cycle *k+1* based on equation (6.1). If the requested slot-size is too large to be fulfilled, instead of v_i, G^{max} will be assigned and this will activate the LT-DBA mechanism. Refer to Case 1 in Fig. 6.3, it shows that the LT-DBA machine will allow extra slot-size to be granted for ONU *i* if adequate amount of free slots occurred (refer to $L_{threshold}$) during the assignment of upstream timeslots for the previous transmission cycle, *k-1* due to frame redirecting at the active RN (refer to Chapters 4 and 5). Due to the reason that the LT-DBA mechanism works better on large amount of redirected traffic at the active RN, if the redirected traffic amount is considered to be small, the LT-DBA will result in a similar performance to that of the standard DBA method and in this case, no additional timeslots can be granted (refer to the Case 2 in Fig. 6.3). Therefore we assume that $L_{threshold}$ has to be at least 2% of the assigned timeslots on previous cycle. Note that this assumption is based on the lowest amount of local intra-subnet traffic, 5%, built in the simulation, while it can be changed based on network behaviour and whether packet scheduling is implemented (packet scheduling can increase the timeslot utilisation that increase the visibility of empty timeslots due to traffic redirection at the active RN).

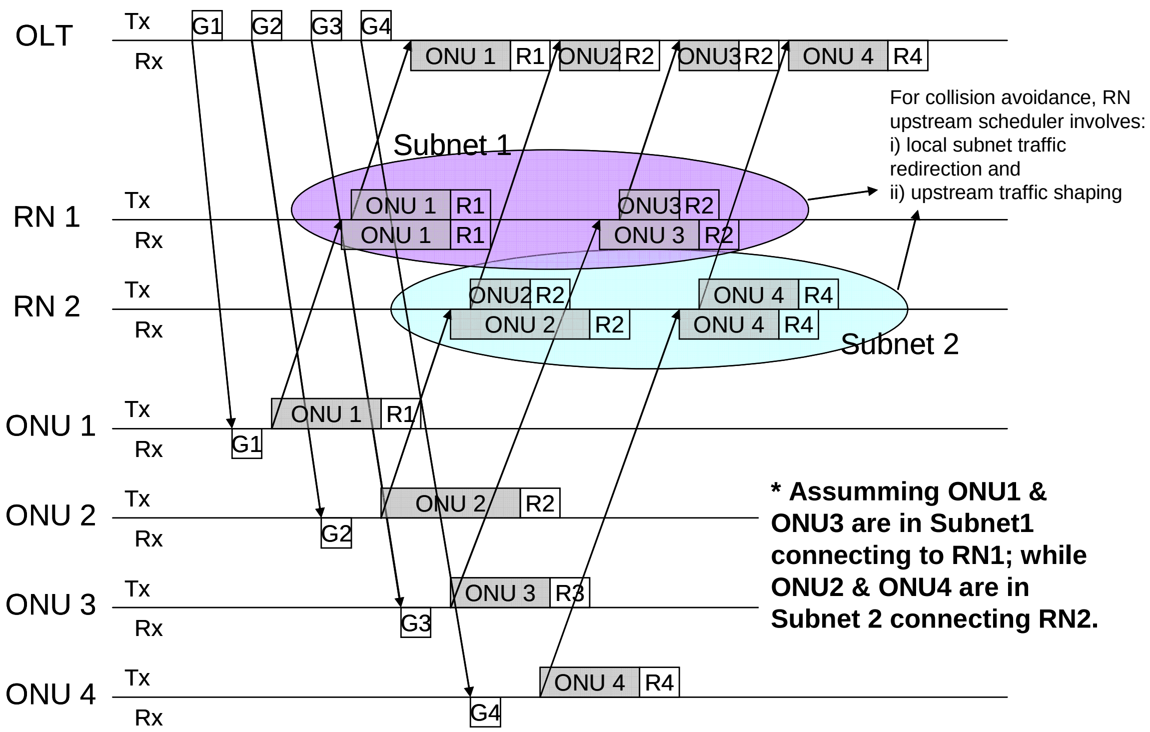

Fig. 6.4: LT-DBA behaviour example on collision avoidance using RN upstream scheduler.

The upstream behaviour of the LT-DBA mechanism is shown in Fig. 6.4. For simplicity and consistency with Fig. 6.1 and Fig. 6.2, four ONUs' upstream transmission behaviours will be elaborated in Fig. 6.4. We assume that ONU 1 and ONU 3 belong to Subnet 1 and connected to RN 1; while ONU 2 and ONU 4 belong to Subnet 2 and connected to RN 2. The timeslot assignment machine at the OLT will use the subnet-based round-robin format to assign timeslots to ONU 1 then ONU 2 followed by ONU 3 and ONU 4 to avoid collision at the passive combiner of the access link (refer to Fig. 6.1). Since ONU 1 and ONU 3 are in the same subnet and the upstream transmissions are separated by upstream transmission of ONU 2 that is in Subnet 2, no collision will occur at the access link's passive combiner due to the additional timeslot allocation. In order to efficiently allocate upstream transmission with the start time for the ONUs based on subnet-based round robin format, the OLT requires information gathering on location of the ONU (which is the information of which ONU is connecting to Subnet 1 and Subnet 2). Therefore, two simple methods are developed for the OLT to discover the ONUs' subnet location in the network without modifying the existing EPON protocol and these methods are discussed in the sub-sections.

6.3.1. Constructing information on ONU location

In order to gather information regarding the physical locations of all the ONUs in the network, the OLT will be required to listen to the information on communications within the whole EPON network and be aware of the presence of the local intra-subnet traffic redirection function at the active RN. This method represents the auto-discovery method of finding which active RN the particular ONU is connected to.

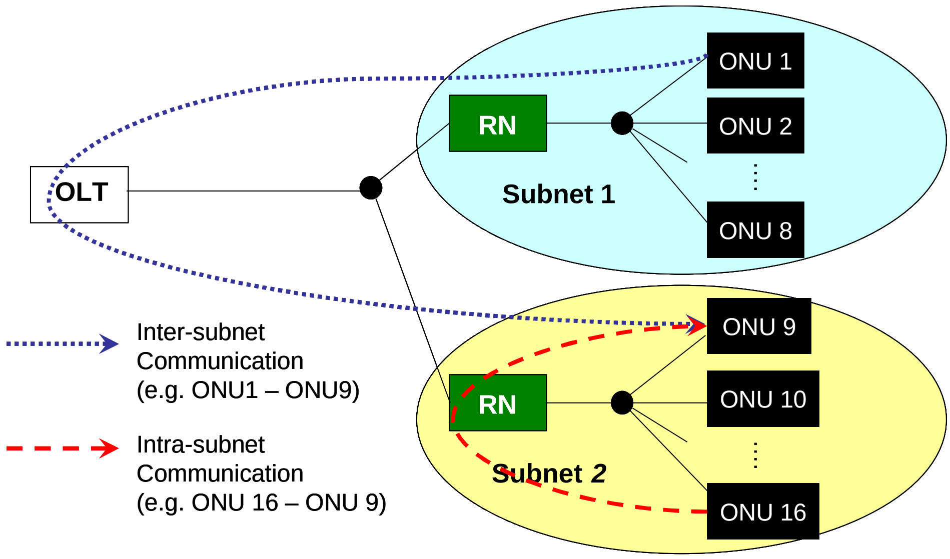

Fig. 6.5: Inter-subnet and intra-subnet transmissions elaborations for information gathering of ONUs physical location.

Refer to Fig. 6.5, inter-subnet communication between ONU 1 and ONU 9 (traffic from ONU 1 with destination of ONU 9) will be going through the OLT, while the intra-subnet communication between ONU 16 and ONU 9 (traffic from ONU 16 with destination of ONU 9) will be redirected at the RN without the need of sending upstream to the OLT. Through this traffic redirection function at the active RN, the OLT is able to determine the subnet location of each ONU corresponding to a particular active RN based on the following:

1) At the initial state, the OLT will assume that all ONU are within the same subnet.
2) If the OLT notices empty timeslot received on a particular time interval that is assigned to ONU *x*, it is assumed that ONU *x* is communicating with the other ONUs within the same subnet and confirm the presence of active RN in the network.
3) If the OLT notices empty upstream timeslot occurred for ONU *x* and receives frames from ONU *x* with destination to ONU y, the OLT will assume that ONU *x* and ONU *y* belong to two different subnets.

Subnet location →

ONU number

TBD	**Known to be in Subnet 1**	**Known to be in Subnet 2**
ONU 1	ONU 2	ONU 10
ONU 3	ONU 7	ONU 12
ONU 4	ONU 8	ONU 16
ONU 5		
ONU 6		
ONU 9		
ONU 11		
ONU 13		
ONU 14		
ONU 15		

Standard DBA (TBD column) | LT-DBA (Subnet 1 and Subnet 2 columns)

*TDB – To be determined

Fig. 6.6: An example of ONUs' subnet location information table in OLT.

Until the OLT receives enough information regarding the physical subnet location of each ONU, it will not activate the LT-DBA mechanism and instead use the standard DBA method. Figure 6.6 shows an example of ONUs' subnet location information table in the OLT memory system. Assume that the OLT notices empty timeslots occurred in the time intervals assigned for ONUs 1, 2, 5, 6, 7, 8, 10, 12 and 16 (which also means that local intra-subnet traffic occur within these ONUs). At the same time, the OLT receives frames with from ONUs, 2, 7 and 8 with destinations to ONU 10, 12 and 16. These information confirm that ONUs 2, 7 and 8 are in a different subnet to ONUs 10, 12 and 16. Therefore, the OLT will form the information table in Fig. 6.6. Hence, LT-DBA is activated for ONUs 2, 7, 8, 10, 12 and 16 while the other ONUs will be using standard DBA since lack of subnet location information. In the latter transmission, the OLT will continue on determining the subnet location of the unknown ONUs in order to fully utilise the LT-DBA method.

The other method of obtaining the ONUs' subnet location is through manually entering the information into the memory of the OLT by a technician. Since the geographical location of the ONUs and the active RN are permanently set during the construction phase of the network, it is possible for the technician to manually insert the information regarding which active RN the particular ONU is connected to. This method requires additional labour cost compared to the auto-discovery and may not be efficient if the MAC and physical LLID addresses require frequent changes.

6.3.2. Collision avoidance at feeder link

Following the solution for collision avoidance at the access link, it is mandatory to ensure that no collision will occur at the feeder link, which is the final passive combiner before reaching the OLT (refer to Fig. 6.1). The collision avoidance solution at this stage is less complicated compared to the one in access link due to the reason of only few active RNs are connected to the passive combiner (two active RNs are assumed in this chapter although more active RNs can be allocated based on network condition).

At very high ONU offered load, the input traffic rate at the ONU is higher than the output rate. The normal DBA algorithm will assign G^{max} to all ONUs if the requesting slot sizes from all ONUs are larger than G^{max} (refer to Fig. 6.3); and this will activate the LT-DBA mechanism to assign excess timeslots for the ONUs with total grant size of G (note that the OLT will only activate LT-DBA for ONUs that have their subnet location known as discussed in the previous sub-section), where G is larger than G^{max}. If the ONUs are transmitting frames in excess timeslots while there is no local intra-subnet traffic (or very less) to be redirected at the active RN; the active RN will transmit all frames upstream to the OLT without noticing that collisions will occur at the passive combiner of the feeder link due to the reason that the total amount of G for all ONUs is larger than 1 Gb/s. As a consequence, an upstream scheduler must be implemented in the active RN to avoid collision event occurring at the feeder link.

Refer to Fig. 6.7, the upstream scheduler is responsible to count the total transmission period for each ONU that is connected to it after the traffic redirection has occurred in the active RN. The active RN will transmit the frames upstream to the OLT with the maximum slot-size of G^{max} for each ONU. Once the active RN has transmitted a number of frames from a particular ONU that is equal to the size of G^{max}, it will buffer the left over frames that can not be transmitted within the current transmission cycle in buffer B6. In the next transmission cycle, as soon as the active RN receives the first upstream frame from a particular ONU where it has left over frames stored in the buffer B6, the buffered frame will be given the priority for transmission due to the following reasons that: i) to ensure that the same upstream transmission sequence from the ONU is maintained compared to EPON without active RN, ii) to prevent buffer overflow in B6 and, iii) to ensure that no frame loss will occur in the active RN, which degrades the system. After receiving all the frames at the OLT, the OLT will not assign additional timeslot on top of standard DBA for the next transmission cycle since there is no free timeslot (or less than the threshold $L_{threshold}$) in the current transmission. This action is designed to avoid buffer overflow at B6 and attempt to empty the buffer at the next transmission cycle since free slots will occur due to intra-subnet traffic redirection in the following transmission cycles.

The above functions assume that the value of G^{max} is known to the active RN. Although the value of G^{max} is directly related to the number of ONUs and fixed for a long period of time, it can change depending on the network behaviour. Fig. 6.8 shows the format of EPON MPCP GATE message. A total number of grants that can be assigned for each ONU are four (four different start times and transmission lengths). Since the active RN listens to all frames that are passing through, the RN can gather the G^{max} information from the GATE message while programming the OLT to send the GATE message with only one number of grant if standard DBA is used and two number of grants if LT-DBA is activated. The grant #1 start time and length denote the value of G^{max} while the grant #2 start time and length represent the amount of excess granting timeslots due to LT-DBA. Hence, the active RN will record the value of G^{max} based on the first grant from the received MPCP GATE message.

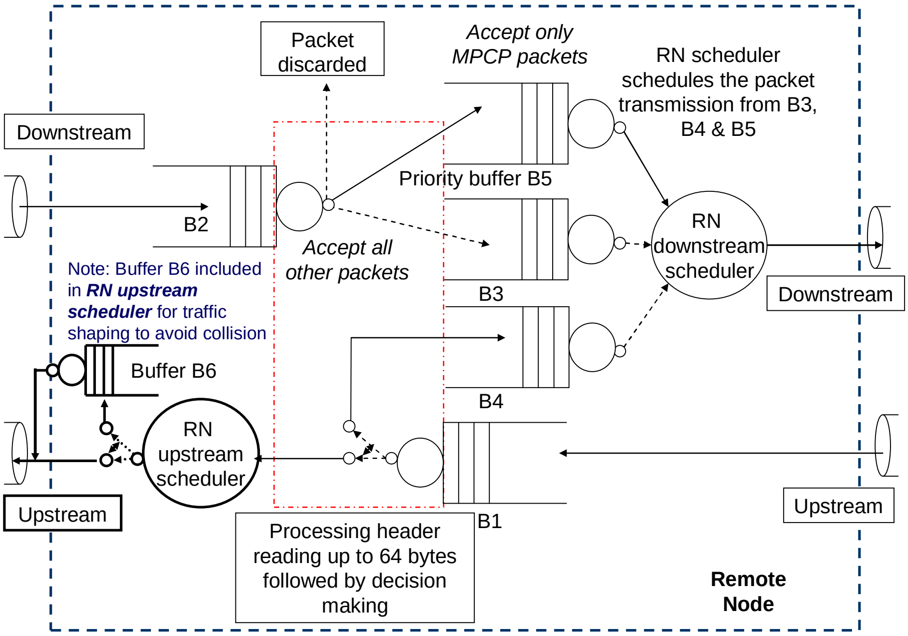

Fig. 6.7: Active RN functional block diagrams with upstream scheduler upgrade.

Fields	Octets/bytes
Destination address (DA)	6
Source address (SA)	Packe
Length/type = 88-08$_{16}$	2
Opcode = 00-02$_{16}$	2
Timestamp	4
Number of grants/flags	1
Grant #1 start time	[4]
Grant #1 length	[2]
Grant #2 start time	[4]
Grant #2 length	[2]
Grant #3 start time	[4]
Grant #3 length	[2]
Grant #4 start time	[4]
Grant #4 length	[2]
Pad = 0	15/39
Frame check sequence	4

Fig. 6.8: EPON MPCP normal GATE message [3-9].

6.4. Simulation Setup

A discrete event simulation of the proposed mechanism was conducted using MATLAB for an EPON with a 1:2:16 architecture. The simulation has been run three times for three different local intra-subnet traffic values; one with LT-DBA, one with limited service DBA (or standard DBA) and one with SBA (or fixed service) for local intra-subnet traffic amounts of 10%, 15% and 20% of the total upstream traffic. Since the LT-DBA is built on top of the EPON with active forwarding RN scheme; two active RNs are used in the simulation with each connecting to eight ONUs to form a subnet as shown in Fig. 6.9. The active RN will perform similar filtering and redirecting functions as described in the previous chapters (Chapters 4 and 5).

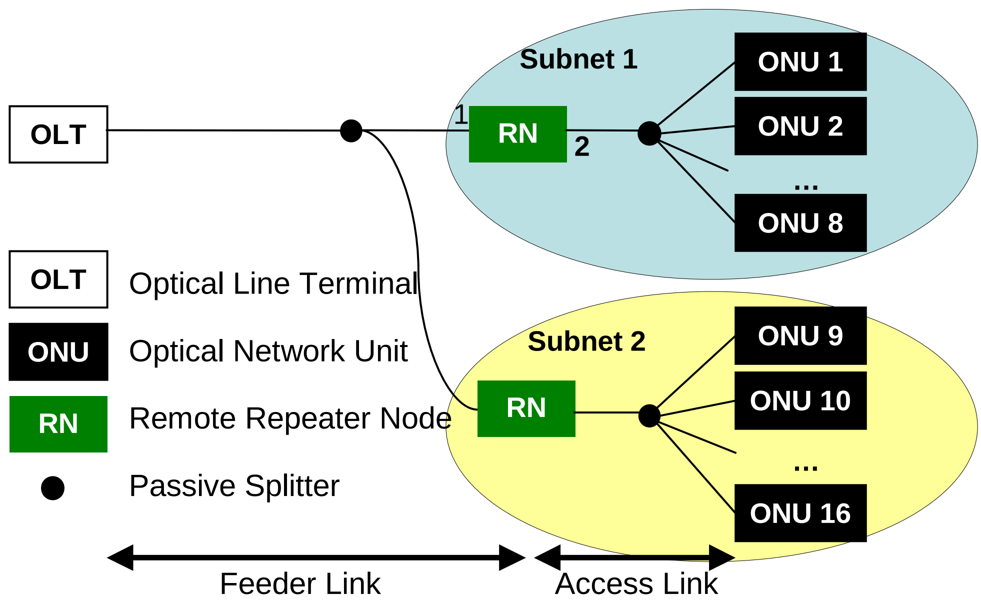

Fig. 6.9: Simulation setup of EPON with active forwarding RNs for LT-DBA evaluation.

The simulation parameters are summarised in Table 6.1. The simulation is built using self-similar synthetic traffic generation with packet sizes uniformly distributed between 64 and 1518 bytes [9]. The EPON link capacity is assumed to be 1 Gb/s for both downstream and upstream and the link rate between the users and ONU is set at 100 Mb/s. The SBA method uses maximum transmission cycle time of 2 ms shared among 16 ONUs regardless of traffic load while the limited service DBA will use dynamically assigned timeslots with the maximum of 2 ms. However for the LT-DBA, the total (summation of) timeslots for all ONU in the network will exceed 2 ms (due to excess granting) but the maximum transmission cycle will be synchronised at 2 ms (with the help of collision avoidance techniques in section 6.3.2).

Parameters	Value
Number of ONUs, *N*	16
EPON line rate (up/down), *C*	1 Gb/s
Link rate of user-to-ONU link	100 Mb/s
Maximum transmission cycle time, T^{max}	2 ms
Guard interval between timeslots, *G*	1 µs
Inter-frame gap (IFG)	96 ns
Laser on/off	512 ns
Automatic Gain Control (ACG)	400 ns
Clock and Data Recovery (CDR)	400 ns
Distance OLT to RN	58 km
Distance RN to ONUs	2 km
Input traffic nature	Self-similar synthetic
RN processing delay	100 µs
ONU buffer size	100 kbytes
Local intra-subnet traffic amount	10%, 15% and 20% out of the total upstream traffic
Packet size	64 – 1518 bytes (uniformly distributed)
Fixed service or static bandwidth allocation (SBA)	$G_{i,k+1} = G^{max} = C\left(\frac{T^{\max}}{N} - G\right)$
Standard dynamic bandwidth allocation (DBA)	Refer to equation (6.1)
Local traffic prediction based dynamic bandwidth allocation (LT-DBA)	Refer to Fig. 6.3.

Table 6.1: Simulation parameters for evaluation of LT-DBA algorithm.

6.5. Simulation Results

In this section, the advantages of LT-DBA in comparison to standard DBA and SBA will be demonstrated in terms of: i) average packet delay, ii) average queue size in ONU, iii) average packet loss ratio and, iv) average upstream data rate per ONU.

6.5.1. Average packet delay

Packet delay represents an important network parameter especially for applications and services that require real-time priority such as voice and video communications, online interactive gaming, IPTV services, etc. The components of the packet delay can be represented as shown in Fig. 6.10 [11] where D_{POLL} represents the time between the packet arrival and the next request message sent by the ONU, D_{GRANT} describes the time interval for an ONU's request for a transmission window until the beginning of the timeslot where this particular frame will be transmitted (note that the D_{GRANT} delay is dynamic as this frame may skip several transmission cycles before it arrives in front of the queue, which directly depends on the ONU traffic load); and D_{QUEUE} characterises the beginning of the timeslot till the beginning of frame transmission. Therefore the packet delay D is equal to

$$D = D_{POLL} + D_{GRANT} + D_{QUEUE} \,. \qquad (6.2)$$

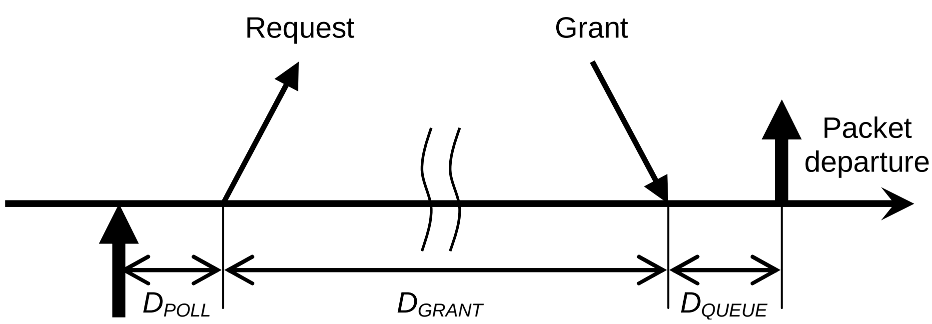

Fig. 6.10: Components of packet delay [11].

The average packet delay as a function of the ONU's offered load is shown in Fig. 6.11. The figure shows that both LT-DBA and standard DBA (limited service) can achieve low delay when the load is low in comparison to SBA. This is due to the reason that constant timeslots will be allocated for each ONU for SBA regardless of the ONU offered load. Therefore, if the

ONU has no frames to send in the upstream timeslot that is assigned to it, the timeslot will be left empty. On the other hand, standard DBA uses dynamic timeslot assignment where light loaded ONUs will receive a smaller timeslot while heavy loaded ONU will be granted a larger timeslot. Therefore, LT-DBA and standard DBA methods can easily outperform the SBA method with low ONU offered load.

At high ONU offered loads of above 0.6, the limited service DBA tends to suffer similar delay as the SBA. However, the LT-DBA can achieve much lower delay at higher traffic loads due to the granting of extra timeslots by LT-DBA algorithm. Furthermore, the performance enhancement is directly related to the amount of local intra-subnet traffic produced at the customer sites. With an increase in local intra-subnet traffic amount (e.g. from 10% to 15% and 20%), the average packet delay will improve due to the reason that more upstream traffic has been redirected at the active RN. The increase of traffic redirection at the active RN will lead the LT-DBA to allocate more extra timeslots to the ONUs.

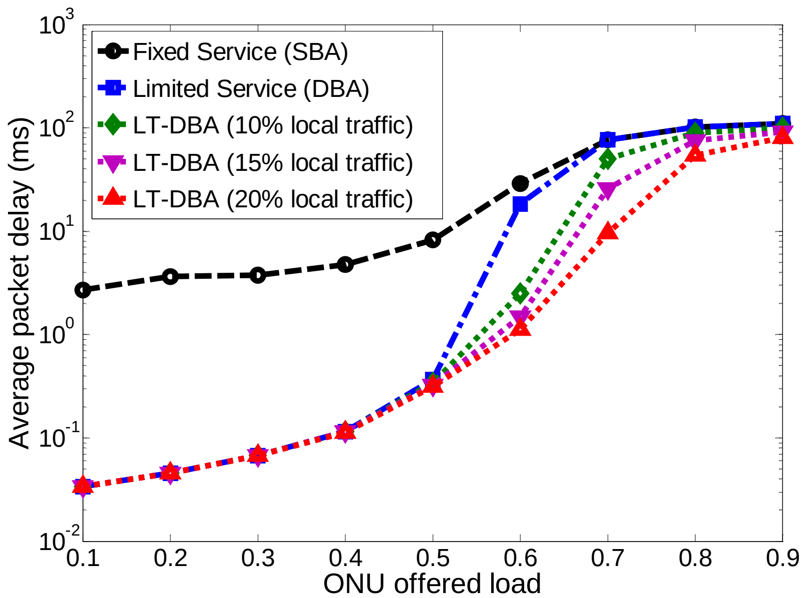

Fig. 6.11: Average packet delay as a function of the ONU's offered load for SBA, limited service DBA, and LT-DBA with 10%, 15% and 20% of local intra-subnet traffic.

At ONU offered load of 0.6, the average packet delay for limited service DBA experiences dramatic increase due to the EPON limitation of 1 Gb/s transmission rate (0.6 load for user-to-ONU link rate of 100 Mb/s for each of 16 ONUs give a value of close to 1 Gb/s). However, LT-DBA uses excess granting technique to allow more timeslots for each ONU to keep low average packet delay. Even though the LT-DBA will still produce higher average packet delay with the increase of ONU offered load, the results have proven a significant improvement compared to SBA and limited service DBA. At ONU offered load of 0.9, the SBA and limited service DBA results in 110 ms average packet delay whereas the LT-DBA service has only 80 ms average delay, which is an improvement of 27% in the average packet delay.

6.5.2. Average queue size

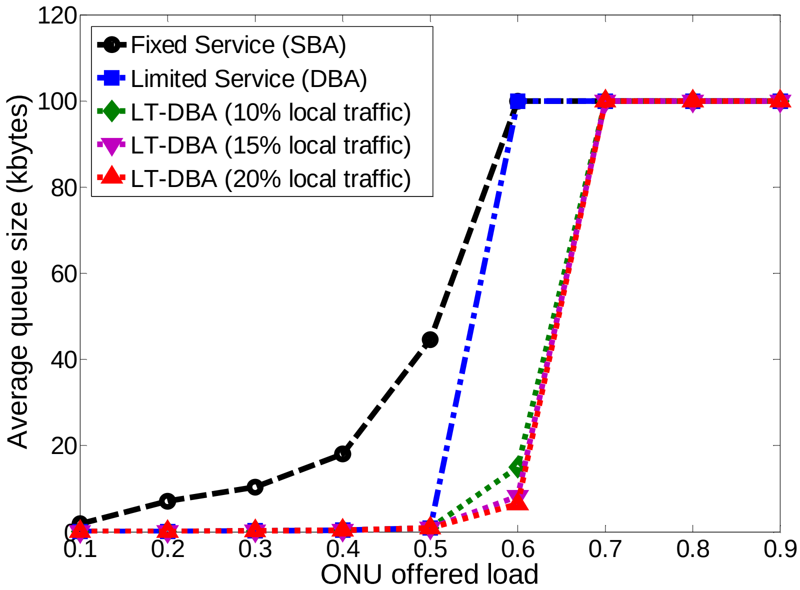

Fig. 6.12: Average ONU queue size as a function of the ONU's offered load for SBA, limited service DBA, and LT-DBA with 10%, 15% and 20% of local intra-subnet traffic.

The average queue size (kBytes) for all 16 ONUs as a function of the ONU's offered load is shown in Fig. 6.12. Due to constant timeslot assigned regardless of the ONU load for the SBA method, the total upstream buffer size of the ONU increases even at low load. Dynamic nature of limited service DBA maintains the queue size at low level until a dramatic increase at around ONU offered load of 0.6 due to the reason that EPON link capacity limitation is met at this load level. However, the LT-DBA allows excess granting of timeslot for ONUs which has local intra-subnet traffic. Therefore, the output rates of the ONUs are larger compared to SBA and limited service DBA methods and hence reduces the queue size in each ONU until the cut-off point with load at 0.7; where external traffic and local inter-subnet traffic have combined to be larger than the EPON link capacity of 1 Gb/s. This result is directly related to the packet loss ratio discussed in the next sub-section. As shown in Fig. 6.12, the average ONU queue size will reach a cut-off point at 100 kbytes, which is the maximum buffer size for each ONU. Therefore, packets arriving after the ONU buffer is full, will be discarded and results in packet loss.

6.5.3. Average packet loss ratio

As presented in Table 6.1, each of the 16 ONUs has an incoming data rate of 100 Mb/s from the connecting users. At high ONU offered load, the total incoming traffic for all ONUs will exceed the EPON limit of 1 Gb/s. Also, the limited buffer size of 100 kbytes in each ONU will quickly overflow and results in packets being dropped. These dropped packets will require a re-transmission from the hosts and degrade the network system. However, LT-DBA's objective is to allow excess granting of timeslots in the presence of local intra-subnet traffic redirection, resulting in increased buffers output rate, and therefore reduce the percentage of packets that has to be dropped.

As shown in Fig. 6.13, standard DBA and SBA will start to encounter frame loss at ONU offered load of 0.5 and the loss ratio will reach as high as 0.34 (which is 34%) at ONU offered load of 0.9. Although the use of LT-DBA can not completely eliminate frame loss at the ONU due to transmission rate limits, it can reduce the frame loss ratio at the ONU to reduce the amount of packet re-transmission required and hence improve the overall network efficiency. Referring to Fig. 6.13, the frame loss ratio will improve by around 5% with each increase of 5% of local intra-subnet traffic amount beginning with 10% of local intra-subnet traffic. At local intra-subnet traffic amount of 20%, the packet loss ratio is reduced to 0.19 (19%) compared to 0.34 (34%) for limited service DBA and SBA, which is a 15% improvement. This improvement is significant as it has reduced 15% of the packets that requires re-transmission for each ONU at very high traffic load.

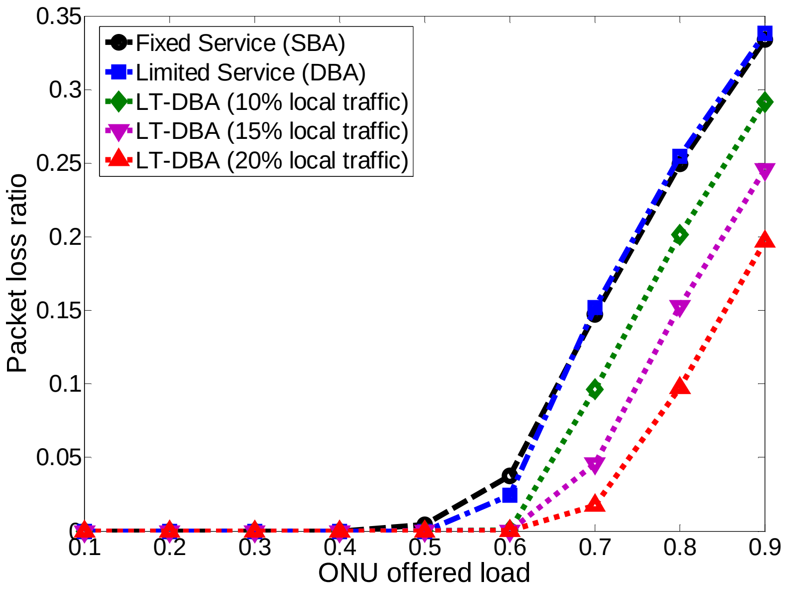

Fig. 6.13: Average packet loss ratio as a function of the ONU's offered load for SBA, limited service DBA, and LT-DBA with 10%, 15% and 20% of local intra-subnet traffic.

6.5.4. Average upstream data rate

To further analyse the improvement achieved through LT-DBA mechanism, Fig. 6.14 shows the average upstream utilisation (data rate) per ONU as a function of the ONU's offered load. At higher ONU loads (> 0.7), the OLT grants the maximum slot-size (G^{max}) to all ONUs and hence the upstream output rate of the ONU in Mb/s is therefore similar for standard DBA and SBA. However, due to more slots being granted in LT-DBA method as a result of local intra-subnet traffic redirection at the active RN, the data rate of the ONU for LT-DBA is much higher compared to the other two services. Similar to the average packet delay results, the increase of upstream data rate available for each ONU is directly related to the amount of local intra-subnet traffic.

Presented in Fig. 6.14, due to less amount of upstream traffic being redirected at the active RN for the case of local intra-subnet traffic of 10%, the upstream data rate is increased only by 4 Mb/s per ONU (63.30 Mb/s for LT-DBA and 59.20 Mb/s for limited service DBA) or 6.7% at ONU offered load of 0.9. However, with the increase of local intra-subnet traffic amount to 20% of the total upstream traffic, the upstream data rate is increased by 13 Mb/s per ONU (72.50 Mb/s for LT-DBA and 59.20 Mb/s for limited service DBA) or 20%

improvement at ONU offered load of 0.9. Although the LT-DBA performance is dependant on the amount of local intra-subnet traffic, the LT-DBA outperforms the conventional standard DBA and SBA methods even at low amount of local intra-subnet traffic.

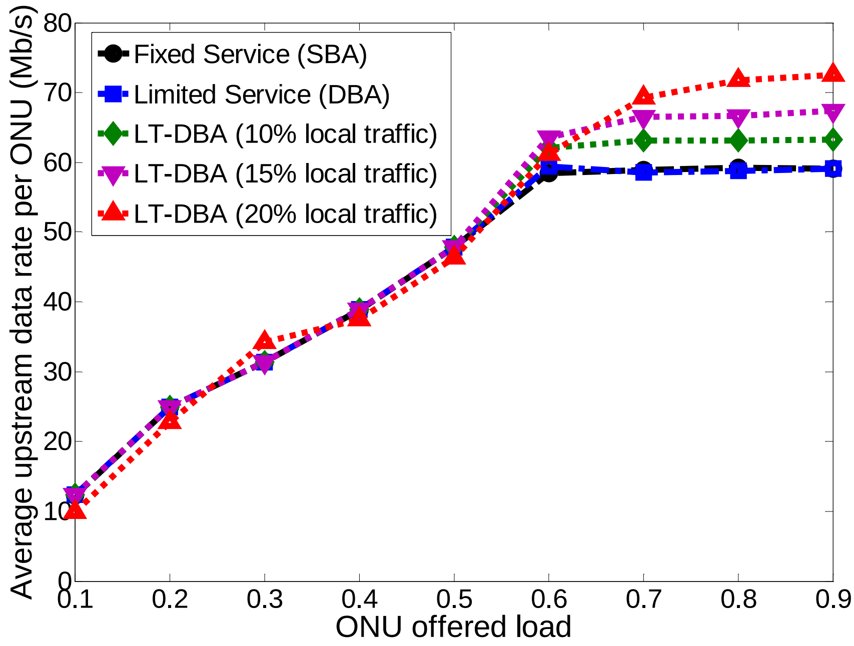

Fig.6.14: Average upstream data rate per ONU as a function of the ONU's offered load for SBA, limited service DBA, and LT-DBA with 10%, 15% and 20% of local intra-subnet traffic.

Summarising the results presented in Fig. 6.11, Fig. 6.12, Fig. 6.13 and Fig. 6.14, the LT-DBA method is proved as an effective DBA algorithm in improving EPON's average packet delay; average queue size, frame loss ratio and average data rate in the upstream direction with the use of RN with active forwarding. Significant amount of improvements such as 20 ms of average packet delay; 20% of upstream data rate increase per ONU and 15% less frame loss at each ONU (for local intra-subnet traffic of 20% at ONU offered load of 0.9) can be achieved compared to standard DBA and SBA methods. EPON incorporating active forwarding RN with LT-DBA architecture is therefore a beneficial augmentation of PON access network that achieves enhanced efficiency that provides a solution for the bandwidth bottleneck in EPON.

6.6. Conclusion

In this chapter, a simple DBA mechanism, LT-DBA, suited for EPON incorporated with repeater based active RN with local intra-subnet traffic redirection technique is proposed to improve the upstream transmission performance from ONU to OLT. The active RN listens to all incoming downstream and upstream frames' headers to gather MAC information of the network and redirect frames based on this information. This technique enables the development of LT-DBA to grant more timeslots to each ONU since substantial amount of the upstream traffic will be filtered and redirected at the RN.

However, excess granting of timeslots can causes collision if collision control mechanism is not used in the active RN. Therefore, we have described two possible mechanisms to avoid collisions at access link and feeder link in section 6.3. In sections 6.4 and 6.5, a discrete event simulation has been conducted on a 16-ONU EPON incorporating active RN. The simulation results show large improvement in upstream packet delay of up to 20 ms, and ONU upstream data rate improvement of up to 13 Mb/s per ONU or 20% improvement. In addition, the excess timeslot granting of LT-DBA results in less packet loss, which is caused by ONU buffer overflow. The improvement of packet loss ratio can be up to 15% at ONU offered load of 0.9 and local intra-subnet traffic of 20%. Therefore the LT-DBA mechanism with EPON incorporated active forwarding RN architecture outperforms fixed service bandwidth allocation method and standard DBA such as limited service IPACT.

6.7. References

[1] G. Kramer, G. Pesavento, “Ethernet passive optical network (EPON): building a next-generation optical access network,” *IEEE Commun. Mag.* Vol 40, no. 2, pp. 66-73, Feb. 2002.

[2] G. Kramer, “Ethernet Passive Optical Networks,” *McGraw-Hill Prof.*, 2004, ISBN: 0071445625, Chapter 5, pp. 45-64.

[3] IEEE 802.3 ah EFM standard, (part of IEEE standard 802.3), available online at http://standards.ieee.org/getieee802/.

[4] G. Kramer, B. Mukherjee, and G. Pesavento, “IPACT: A Dynamic protocol for an Ethernet PON (EPON),” *IEEE Commun. Mag.*, vol. 40, no. 2, pp. 74-80, Feb. 2002.

[5] C. M. Assi, Y. Ye, S. Dixit, M. A. Ali, “Dynamic Bandwidth Allocation for Quality-of-Service Over Ethernet PONs,” *IEEE J. Sel. Areas Commun.*, vol. 21, pp. 1467-1477, Nov. 2003.

[6] S. Hwang, Z. D. Shyu, L. Y. Ke, C. C. Chang, “A novel early DBA mechanism with prediction-based fair excessive bandwidth allocation scheme in EPON,” *Computer Communications*, vol. 31, no. 9, pp. 1814-1823, Jun. 2008.

[7] M. P. McGarry, M. Reisslein, and M. Maier, “Ethernet Passive Optical Network Architectures and Dynamic Bandwidth Allocation Algorithms,” *IEEE Commun. Surveys and Tutorials*, vol. 10, no. 3, pp. 46-60, 2008.

[8] Shami, X. Bai, N. Ghani, C. M. Assi, H. T. Mouftah, “QoS Control Schemes for Two-Stage Ethernet Passive Optical Access Networks,” *IEEE J. Sel. Areas Commun.*, vol. 23, no. 8, pp. 1467-1477, Aug. 2005.

[9] G. Kramer, “Ethernet Passive Optical Networks,” *McGraw-Hill Prof.*, 2004, ISBN: 0071445625, Chapter 8, pp. 85-138.

[10] M. S. Taqqu, W. Willinger, R. Sherman, “Proof of a fundamental result in self-similar traffic modelling,” *ACM/SIGCOMM Comp. Comm. Rev.* Vol. 27, pp. 5-23, 1997.

[11] G. Kramer, “Ethernet Passive Optical Networks,” *McGraw-Hill Prof.*, 2004, ISBN: 0071445625, Chapter 16, pp. 215-236.

[12] IEEE802.1p standard, “Supplement to MAC Bridges: Traffic Class Expediting and Dynamic Multicast Filtering,” part of IEEE 802.1D.

[13] IEEE 802.1Q standard, “Virtual Bridged Local Area Networks”.

[14] B. Mukherjee, “Optical WDM networks,” *Springer*, ISBN: 0387290559, chapter 5.

[15] M. R. Radivojevic, P. S. Matavulj, “Implementation of Intra-ONU Scheduling for Quality of Service Support in Ethernet Passive Optical Networks,” *J. Lightwave Tech.* vol. 27, no. 18, pp. 4055-4062, Sept. 2009.

[16] G. Kramer, A. Banerjee, N. K. Singhal, B. Mukherjee, S. Dixit, Y. Ye, “Fair queuing with envelopes (FQSE): a cousin-fair hierarchical scheduler for subscriber access networks,” *IEEE J. Sel. Areas in Commun.*, vol. 22, no. 8, pp. 1497 – 1513, Oct. 2004.

[17] N. Ghani, A. Shami, C. Assi, M. Y. A. Raja, “Intra-ONU bandwidth scheduling in Ethernet passive optical networks,” *IEEE Commun. Lett.*, vol 8, no. 11, pp. 683-685, Nov. 2004.

[18] G. Kramer, “Ethernet Passive Optical Networks,” *McGraw-Hill Prof.*, 2004, ISBN: 0071445625, Chapter 14, pp. 189-200.

7 Evaluation of 10/1 Gb/s EPON Incorporating Active RN

7.1. Introduction

The access network, which delivers broadband services and applications to the end users, always remains an important part in all communications networks for ensuring the end-to-end quality of service (QoS). Since the deployment of passive optical network (PON) systems, the end users are able to enjoy large bandwidth and high-quality services. Thirty million lines have been deployed worldwide and the rate of Ethernet PON (EPON) deployments is accelerating, since the standardisation of 1 Gb/s EPON in year 2004 [1]. This wide adoption of 1 Gb/s EPON provides a significant jump in access network capacity, which allows internet service providers (SPs) to deploy advanced digital video services [2]. For example, in Japan, Kokusai Denshin Denwa International (KDDI) is offering digital versatile disc (DVD) grade multi-channel broadcasting and video-on-demand (VoD), as well as high-grade IP telephony and high-speed Internet connections [2]. Furthermore, the introduction of killer applications such as Internet protocol television (IPTV), video-on-demand (VoD), video conferencing and interactive gaming, which are enabled by gigabit-capable optical access networks, have been accepted by the subscribers with great enthusiasm and driven up the demand for more bandwidth-intensive applications and services such as high-definition television (HDTV) that will consume 8 ~ 10 Mb/s per channel [2]. As a consequence, the current IEEE 802.3ah 1 Gb/s symmetric EPON standard [3-5], is only considered sufficient for a short period of time [2, 6]. SPs have to start looking for ways to increase the channel capacity and the number of customers.

In year 2006, IEEE 802.3av Task Force was formed to standardise the 10G-EPON upgrade and it is expected to be completed by year 2009 [7-10]. In Chapter 2, the efficiency of 10G-EPON system and the upgradeability and coexistence with existing 1G-EPON have been discussed. Since the development strategy of 10G-EPON must be co-existent with the conventional 1G-EPON, the operation mode of the new 10G-EPON system is a combination of 1Gb/s downstream/1 Gb/s upstream, 10 Gb/s downstream/1 Gb/s upstream, and 10 Gb/s downstream/10 Gb/s upstream over the same optical distribution network (ODN) [11]. The next-generation EPON system migration will begin from 1G-EPON to asymmetric 10 Gb/s downstream and 1 Gb/s upstream system before finally migrating to full 10 Gb/s EPON.

In order to receive 10 Gb/s downstream service, each ONU transceiver port will require an upgrade to support 10 Gb/s operation following the typical path of 10 fold capacity increase at 3 times the port price [9]. In a large access network that supports a large number of ONUs, an upgrade of each ONU's port to support 10 Gb/s or 'full upgrade' is costly. Furthermore, it is almost impossible for each ONU to receive full 10 Gb/s data rate, especially at high traffic load due to the reason that the link capacity is shared between all ONUs in the network. In this chapter, the use of active remote repeater node (RN) with layer two filtering scheme is proposed for asymmetric 10 Gb/s EPON upgrade. An evaluation of the scheme is presented in terms of cost-structure and downstream throughput per ONU compared to full upgrade. The rest of the chapter is organised as follows: Section 7.2 discusses the options for 10 Gb/s downstream upgrade for next generation EPON. Section 7.3 gives a detailed explanation on the use of active RN in EPON as a cost-effective solution for asymmetric 10 Gb/s downstream and 1 Gb/s upstream EPON system upgrade. Section 7.4 presents the network simulation results and cost analysis with discussions. Finally section 7.5 summarises the overall chapter.

7.2. EPON 10 Gb/s Downstream Upgrade

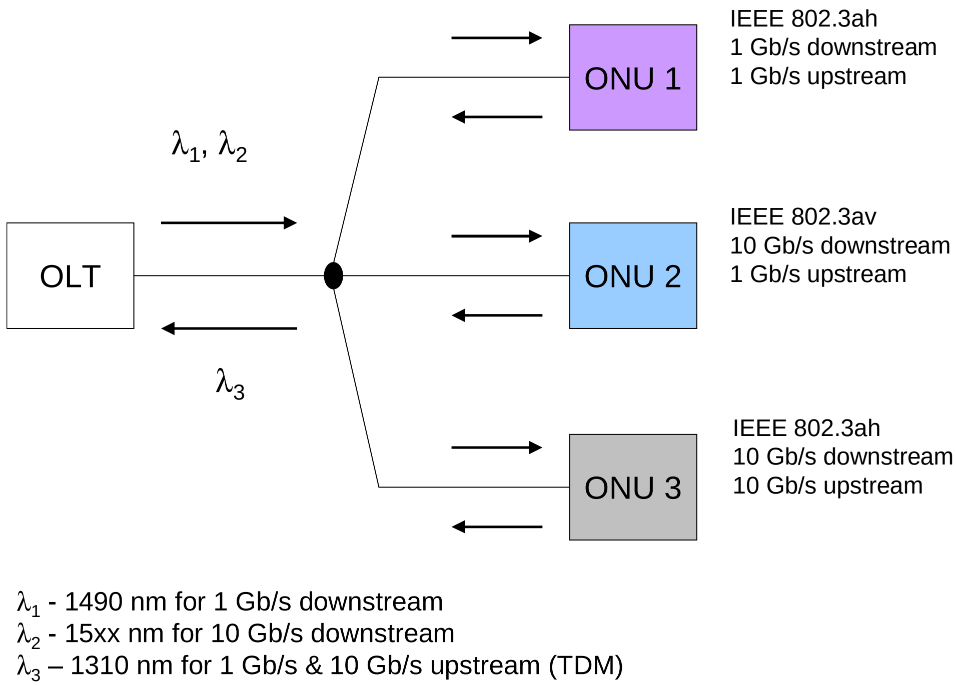

Fig. 7.1: IEEE 802.3av Task Force proposed 10 Gb/s EPON upgrade.

According to the IEEE 802.3av task force, the downstream 1 Gb/s and 10 Gb/s data streams in the emerging, next-generation EPONs will be wavelength-division-multiplexed (WDM), which creates two independent continuous point-to-multipoint channels, separated by a large bandwidth gap that allows uninterrupted operation under any temperature conditions [12]. Several other schemes such as signal mixing for 1Gb/s and 10 Gb/s into one wavelength, orthogonal polarisation multiplexing and the combined use of intensity modulation and differential phase-shift keying transmission to overlay both 10 Gb/s and 1 Gb/s signals into current 1490 nm wavelength [13], have been suggested. These solutions can be complex and are practically hard to implement due to the reasons that the existing 1G-EPON is not able to support 10 Gb/s speeds and additional resources (both hardware and software) are needed if these methods are used, which further increase the upgrade cost [13]. Therefore, the 1 Gb/s downstream link will remain at 1490 nm with the 20 nm window size (in accordance with the IEEE 802.3-2005), and the wavelength of 1550 nm will remain reserved as downstream video [4]. The new 10 Gb/s downstream link is planned to be allocated in the 1570 nm to 1600 nm window, which depends on both the availability of the laser sources for the OLT and on the optical filter design options and their compatibility with deployed legacy systems [9]. The allocation of separate wavelength at the 1570 nm to 1600 nm window for 10 Gb/s downstream channel is currently considered as the best available option by the task force, mainly due to its limited non-linear impairments and lower 10 Gb/s signal degradation [14].

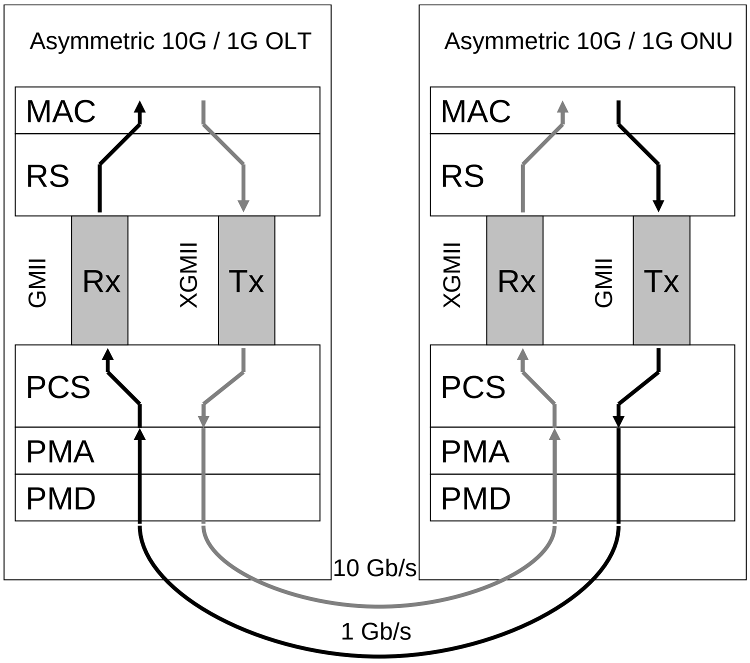

Fig. 7.2: Asymmetric 10 G/1 G EPON implementation showing the new IEEE 802.3av layering model. Please refer to Chapter 2 for details of sub-layers functions (MAC – medium access control, RS – reconciliation sub-layer, PCS – physical coding sub-layer, PMA – physical medium attachment, PMD – physical medium dependent, GMII – gigabit media independent interface).

Coexistence of 1G-EPON and 10G-EPON is a crucial consideration in such a WDM upgrade option. As shown in Fig. 7.2, additional gigabit media independent interface (GMII) termed XGMII is proposed to be implemented at the OLT and ONU physical port to support 10 Gb/s downstream transmission [15]. The XGMII specifies an interface between a 10 gigabit-capable medium access control (MAC) and a gigabit physical layer (as discussed in Chapter 2). From Fig. 7.2, it is shown that the 10 Gb/s receiver port upgrade is mandatory to all new 10 Gb/s downstream enabled ONU. Although the transceiver ports upgrade is expected to follow the path of 10 fold capacity increase at 3 times the port price, the upgrade becomes expensive when the number of ONUs increases. Furthermore, the downstream data rate of each ONU will be limited in a large scale EPON, since the 10 Gb/s downstream transmission link rate that is shared among all ONUs. For example, at high traffic load hour where 10 Gb/s downstream EPON link rate is equally shared among 32 ONUs, each can only reach a maximum throughput of 312.5 Mb/s. This downstream throughput is further reduced to 156.25 Mb/s and 78.125 Mb/s for 64 and 128 ONUs on a 10 Gb/s link. This limitation directly reduce the return on investment (ROI) spent on ONU upgrade.

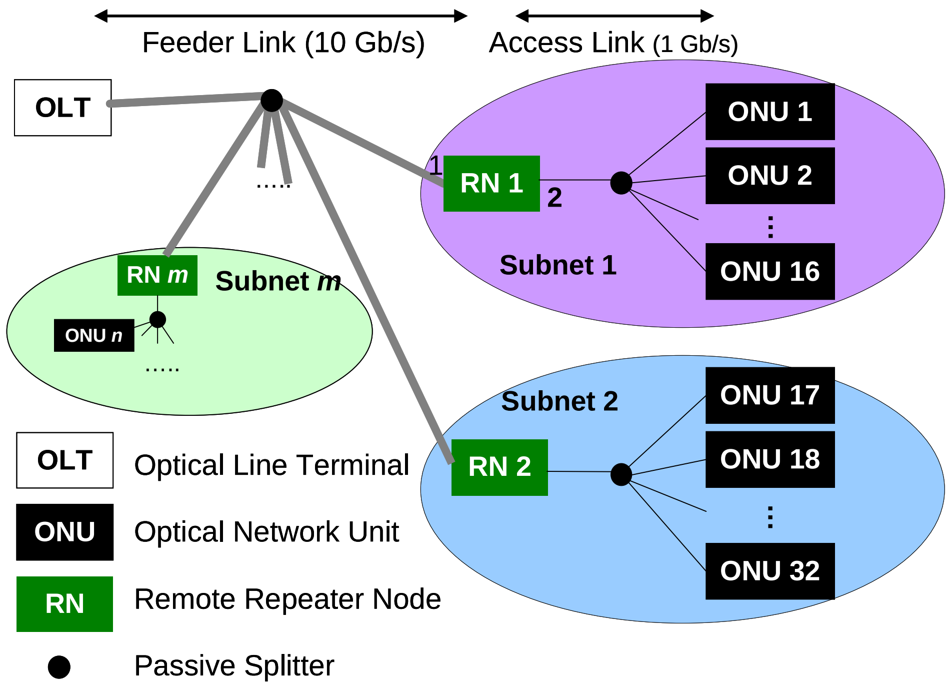

Fig. 7.3: The proposed 10/1 Gb/s asymmetric EPON upgrade using active RN (showing upgrade on feeder link between OLT and RNs while keeping the access link between RNs and ONUs at conventional 1 Gb/s) to reduce the initial capital upgrade cost.

In the previous chapters, we demonstrated that the EPON network architecture incorporating active RN has the advantages of improving downstream and upstream performances due to the two functions of the active RN's, namely 1) downstream traffic filtering and 2) local intra-subnet traffic redirecting. The first function of the active RN can be used to design an EPON with active RN architecture that supports 10 G/1 G EPON. The network architecture is shown in Fig. 7.3 where *n* ONUs are allocated equally to *m* RNs forming *m* subnets. The advantages of the proposed scheme are:

1) Downstream 10 Gb/s upgrade is required only between OLT and *m* RNs compared to all *n* ONUs in full upgrade, which greatly reduce the investment cost since *n* is much greater than *m* (e.g. 160 ONUs compared to 10 RNs).
2) At high traffic load where the downstream capacity is shared among *n* ONUs, similar ONU downstream data rate can be achieved with the proposed scheme compared to full upgrade (e.g. when 10 Gb/s is shared among 160 ONUs; where 1Gb/s ONU port is sufficient due to RN's filtering).

In the next section, the detailed functions of the active RN towards supporting 10 Gb/s EPON downstream upgrade will be discussed.

7.3. Active RN Design for 10 Gb/s EPON Upgrade

Similar to the proposed network architecture in the previous chapters, the active RN incorporating a repeater is designed to satisfy the power budget constraints imposed by longer reach, high split-ratio and low dynamic range ONUs based on vertical cavity surface emitting laser (VCSEL) transmitter and receivers [16]. However given that the active node now provides access to electronic physical layer, a simple layer two (MAC) filtering technique can be integrated into this active RN to reduce the access link bandwidth (in contrast to both filtering and local traffic redirecting techniques in the previous chapters). In order to process traffic filtering, the active RN requires accurate information regarding the connected devices. By listening to all the incoming frames' header information (including Multipoint Control Protocol, MPCP frames), the active RN is able to form an information table to identify the MAC and LLID addresses of the connecting ONUs in each subnet. This information table is used to filter frames that are not destined to the customer units beyond the active RN; while appropriate frames will be forwarded to the respective customer units serviced by the active RN under the condition that this proposed technique will not affect the current MPCP and future upgrade for IEEE 802.3av standard.

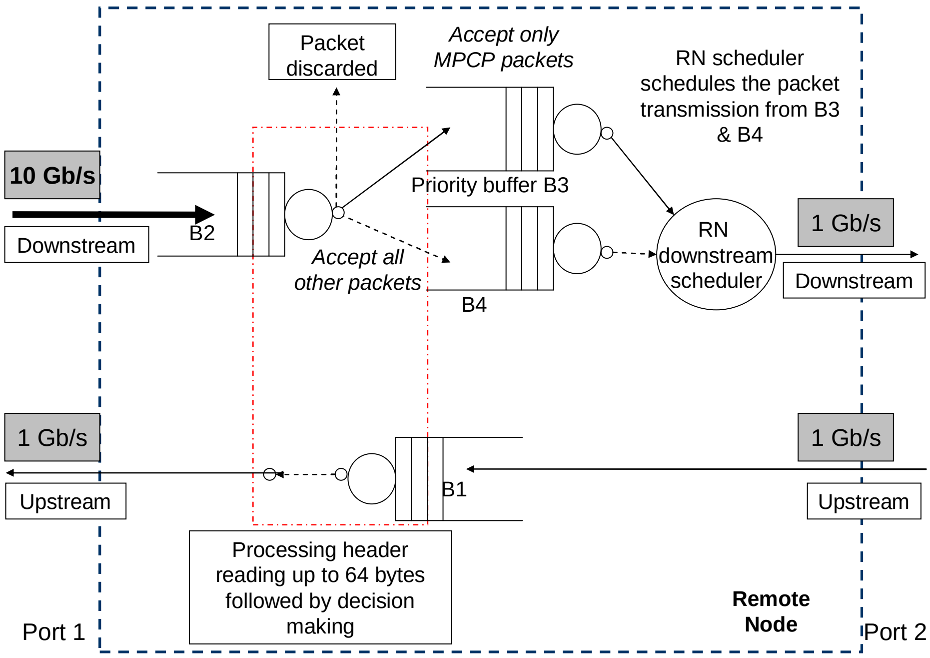

Fig. 7.4: Active RN functional block diagram for proposed cost-effective 10 G/1 G EPON upgrade.

At the initial stage where an ONU has not registered to the network, the OLT will register the ONU through the MPCP auto-discovery mode in order to send traffic downstream to it. Once the registration is completed, the active RN should have included the addresses for the newly registered ONU through listening to all MPCP frames to guarantee precise traffic filtering. Furthermore, the technique is built under the conditions of no functional and hardware changes will be applied to the large number of ONUs (where the ONUs port rate stays at 1 Gb/s while the OLT requires an upgrade to 10 Gb/s for the downstream).

A simplified version (compared to Chapters 4, 5, and 6) of the active RN functional block diagram used in the asymmetric 10 Gb/s upgrade is shown in Fig. 7.4. In the downstream direction, the OLT transmits downstream traffic at a rate of 10 Gb/s. In the active RN, the downstream data will be buffered at B2 as it takes a fixed time to process the header reading of up to 64 bytes (read destination MAC, LLID and source MAC addresses to determine the destination of the frame to be either discarded or transmitted downstream to the ONUs). Same header reading process occurs in upstream direction except the transmission rate is in 1 Gb/s and is used in updating the information table for knowing which ONU is connected to the RN. Also, note that MPCP frames will be inserted into priority buffer B3 and all other accepted frames will be stored in buffer B4 due to the reason that the MPCP frames contain timing information that achieve synchronisation between the ONUs and OLT. This information is important for the ONUs to accurately transmit frames upstream in order to avoid collision at the passive combiner. Therefore the use of the RN scheduler and the assignment of constant wait time to MPCP frames are aimed at achieving negligible delay variability in the downstream path (refer to discussion in the Chapter 6). Once a MPCP frame is accepted into buffer B3, the RN scheduler will make sure the frame undergoes a wait time, which leads to a constant delay for MPCP packets and the ranging and synchronisation between the OLT and ONUs will not be affected (details refer to Chapter 6).

During the wait time, the RN scheduler will insert packets from buffer B4. Since the downstream transmission rate from the RN to the connecting ONUs is limited at 1 Gb/s, a bottleneck will occur at the RN if burst traffic to the same location occurs. Therefore, buffer size of B4 represents an important element in the proposed cost-effective asymmetric 10G-EPON upgrade using active filtering RN, which will be discussed in the next section. The summary of the frame filtering technique in the RN is shown in Fig. 7.5. Note that the RN needs to read only the first 64 bytes of the frame header to determine the source and destination addresses. Therefore a fixed processing delay will be implemented at the RN for both downstream and upstream pass-through traffic hence again the ranging in EPON will not be affected.

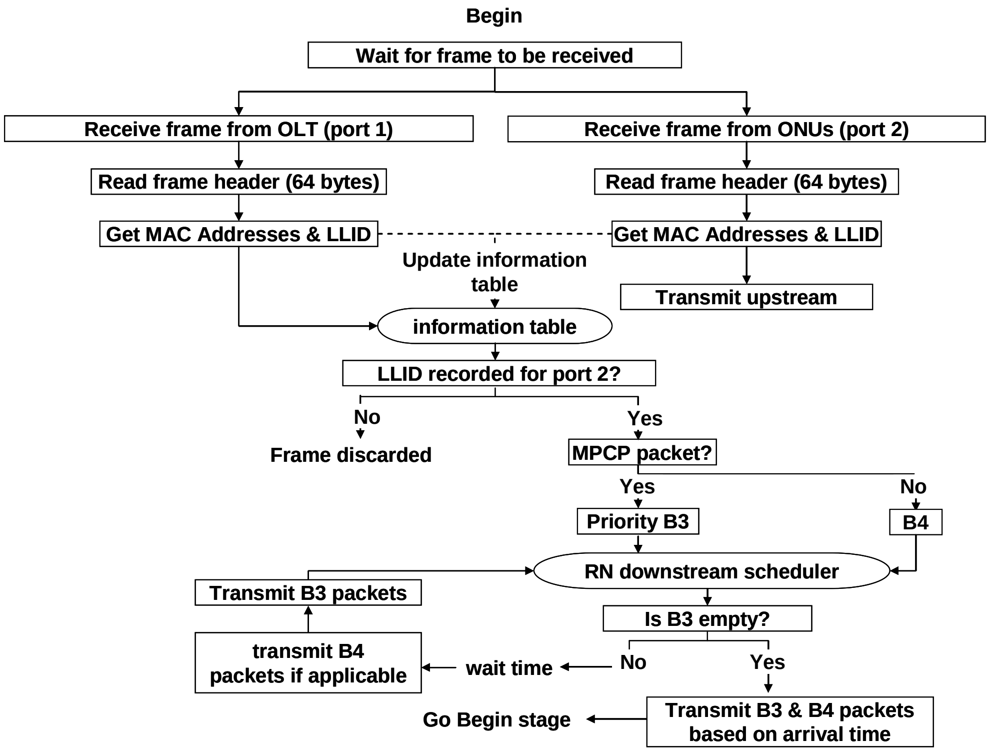

Fig. 7.5: Frame filtering flow chart in the active RN for asymmetric 10 Gb/s downstream and 1 Gb/s upstream EPON system.

7.4. Simulation Results and Discussions

Parameters	Value
Number of ONUs	160
Number of RN	10
Number of ONU/RN	16
OLT output port rate (downstream)	10 Gb/s
OLT input port rate (upstream)	1 Gb/s
RN ports rate	10 Gb/s (from OLT) 1 Gb/s (from ONU)
Transmission cycle time	2 ms
Distance OLT to RN	58 km
Distance RN to ONUs	2 km
Share buffer size	600 kBytes (refer to Fig. 7.6)
Input traffic nature	Self-similar synthetic
RN processing delay (t_1)	100 μs
Packet size	64 – 1518 bytes (uniformly distributed)

Table 7.1: Simulation parameters.

A discrete simulation of the proposed EPON incorporating active RN for 10 Gb/s downstream upgrade architecture was conducted using MATLAB with the 1:10:160 architecture (ten subnets with each connected to a RN). The reason why 10 subnets architecture is chosen is discussed in sub-section 7.4.2 though subnet number of larger than 10 will also lead to similar data rates compared to EPON without active RN upgrade (full upgrade). Two sets of simulation were completed, one with RNs and one without RNs. It is assumed that the average amount of traffic transmitted to the ten subnets is equal. Therefore, the performance of using and without using the RN can be evaluated by simply comparing the network performance of any one subnet. Due to asymmetric upgrade of 10 Gb/s downstream and 1 Gb/s upstream in this proposed architecture, the upstream transmission will be using 1 Gb/s dynamic bandwidth assignment (DBA) method as in Chapters 4, 5, 6 and [17, 18], hence will not be discussed here. The simulation parameters are summarised in Table 7.1. The simulation is built using self-similar synthetic traffic generation with packet sizes uniformly distributed between 64 and 1518 bytes [19]. The link capacity is assumed as 10 Gb/s downstream (transmission link rate between the OLT and the active RN is set at 10 Gb/s while the transmission link rate between active RN and ONUs is at 1 Gb/s) and 1 Gb/s upstream. The distance from OLT to each ONUs is set at 60 km (since a remote node is built on top of a repeater which extends the distance of the PON up to 60 km [16]). The transmission cycle time is 2 ms since the upstream transmission remains at 1 Gb/s and the processing delay for pass-through traffic at the active RN is set at 100 μs.

7.4.1. RN frame loss rate and buffer size

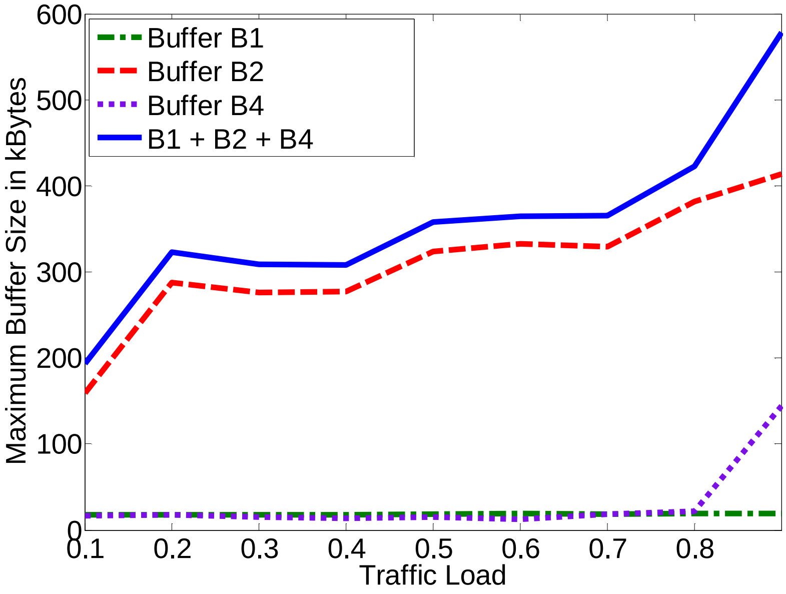

Fig. 7.6: Maximum buffer size for B1, B2, B4 and total RN buffer size (assuming B3 is almost negligible).

As shown in Fig. 7.4, the buffers represent important elements in the RN to store downstream frames pending transmission (B4), and downstream traffic while the frame header is being processed (B2). The maximum total buffer size recorded (B1+B2+B4 since B3 is almost negligible) is shown in Fig. 7.6 while buffer B1 represents the upstream traffic while the frame header is being processed. Overall, there is no one particular period where the maximum buffer size is larger than 580 kBytes. Therefore, the total buffer size in the simulation is set at 600 kBytes with first-in-first-out (FIFO) structure, and hence there is no frame loss in the RN. Please note that this setting is only feasible for traffic shared equally among all subnets in peak traffic hours. If dominating subnet on downstream traffic exists with bursty traffic, the buffer size requirement becomes much higher. However, this can be controlled by the DBA scheduler in the OLT for traffic shaping. It is important that the active RN implementation will not impact the current working EPON system. If there is a frame loss in the RN, the ONU or OLT will need to retransmit the lost packets, which results in decreasing network efficiency. Therefore, keeping the frame loss rate to negligible levels is crucial in EPON with active RN implementation. Fig. 7.6 shows that the buffer B2 dominates the total buffer size due to the reason that arriving downstream data stream are required to be stored pending header processing. This buffer size is directly related to the active RN's processing delay where in this simulation, it is assumed to be 100 μs. By reducing the RN processing delay, the total buffer size can be reduced. Furthermore, buffer B4 suffers a sharp increase at traffic load of 0.9 as the 1 Gb/s capacity limit is reached (recall the access link capacity between the RN and connecting ONUs is 1 Gb/s).

7.4.2. Asymmetric 10G-EPON with active RN architecture

Without the use of active RN in EPON, full upgrade is required for each ONU to upgrade the port rate in order to process 10 Gb/s data stream. However, the proposed scheme requires an upgrade only at the feeder link (between OLT and the active RNs as presented in Fig. 7.1) to 10 Gb/s and remainder of the access link (between the active RNs and ONUs) remains at 1 Gb/s in order to reduce the total upgrade cost. Since the downstream output rate of each RN is 1 Gb/s, a total number of *n* ONUs is required to be allocated to different RNs in order to achieve the same downstream data rate per ONU compared to full upgrade. If the network is operated at full load, the average data rate per ONU, *R* (in Mb/s) using EPON with active RN upgrade can be described as:

$$R = \min\left[\frac{m \cdot C_{access}}{n}, \frac{C_{feeder}}{n}\right] \qquad (7.1)$$

where C_{access} represents the link capacity between RNs and ONUs, which is 1 Gb/s and the C_{feeder} represents the link capacity between OLT and RNs, which is at 10 Gb/s and *m* represents the total number of RN (or subnets) required. As equation (7.1) suggests, the downstream data rate per ONU is either limited by C_{access} or C_{feeder}. For example, if $m = 2$ RNs, each subnet is only capable of processing 1 Gb/s downstream data rate (with a total of 2 Gb/s for 2 subnets) despite the feeder link capacity is at 10 Gb/s. Therefore a minimum of $m = 10$ RNs is required to maintain equal downstream *R* for both EPON with RN and full upgrade architectures to satisfy $m \cdot C_{access} = C_{feeder}$. Although the value of *m* can be larger than 10, it is not recommended since installing more active RN will introduce higher costs. However, the value of *n* (the number of ONUs connecting to each active RN) can be increased but will constraint the bandwidth shared per user.

7.4.3. Cost-effective 10G-EPON with RN architecture

Table 7.2 shows an example of current 1G-EPON component costs [20]. Please note that the evaluation covers the initial components' upgrade costs which exclude the operational and maintenance costs. Assuming the ONU port price is dominated in the unit cost; upgrading each ONU to support 10 Gb/s transmission rate will require an upgrade cost of approximately $480/ONU following the Ethernet hardware rule of 10 fold capacity increase at 3 times the port price. In addition, the OLT will require an upgrade cost of approximately $10,800 (Note that only downstream 10 Gb/s upgrade is discussed while upstream transmission remains at 1 Gb/s for asymmetric upgrade).

Parameters	Value
OLT Costs	
Enclosure cost ($)	200000 (Urban) 160000 (Suburban)
Input port rate (Mb/s)	1000
Input port cost ($)	4240
Output port rate (Mb/s)	1000
Output port cost ($)	3600
10 Gb/s downstream port upgrade ($)	10800
ONU Costs	
Install cost ($)	96
ONU unit cost ($)	160
10 Gb/s receiving port upgrade ($)	480
RN Costs	
Install cost ($)	96
1 Gb/s port upgrade ($) (to ONUs)	160
10 Gb/s port upgrade ($) (from OLT)	480

Table 7.2: EPON component costs [20].

Fig. 7.7 shows the total downstream upgrade cost for progressive upgrade cases of 16 ONUs per RN and 32 ONUs per RN (e.g. if the ONU number is 64, 4 RNs are needed for 16 ONUs per RN progressive upgrade while 2 RNs are needed for 32 ONUs per RN progressive upgrade) as well as full upgrade of up to 512 ONUs. The total upgrade cost includes the OLT output port upgrade cost of \$10,800, the RN installation and upgrade cost of \$740 (10 Gb/s port and 1 Gb/s port) and ONU upgrade cost of approximately \$480 per ONU. Once off upgrade (EPON with all RN without a progressive upgrade) to install a sufficient amount of active RN into the network is another cost-effective upgrade method but this solution is dependant on the number of ONU that will be supported by each RN (refer to equation (7.1) in subsection 7.4.2). It is assumed that the active RN will require an installation cost and unit cost similar to the ONU although it provides much simpler function than that. Therefore, the 10 Gb/s downstream upgrade costs for EPON with active RN architecture will not have significant cost saving at low number of ONU. However as the EPON system scales to cover more customer units, the cost of full upgrade to each ONU's receiving port increases linearly while the cost of EPON with active RN upgrade (both progressive upgrade scenarios) experience much lower cost since an amount of 16 or 32 ONUs will only require only one RN. At n = 160, the full upgrade on each ONU requires an upgrade cost of \$87,600 compared to \$18,200 of EPON with RN upgrade (16 ONUs per RN). For existing deployed 1:16 and 1:32 conventional small scale EPON systems, several PON can be combined to produce a large scale PON system utilising the advantages of the RN to provide lower initial upgrade cost (since the repeater provides sufficient power budget for high split-ratios and long reach, where the advantages are presented in Chapter 5).

Having the low upgrade cost for EPON with active RN architecture, the simulation results in Fig. 7.8 proves that an equal downstream data rate per ONU can be achieved for both EPON with active RN upgrade and full upgrade architectures. The small difference of 0.2 Mbps per ONU is due to processing and scheduling delays in the active RN that is currently assumed to be 100 μs (similar to 1 Gb/s system), which can be reduced to suit the 10 Gb/s operation.

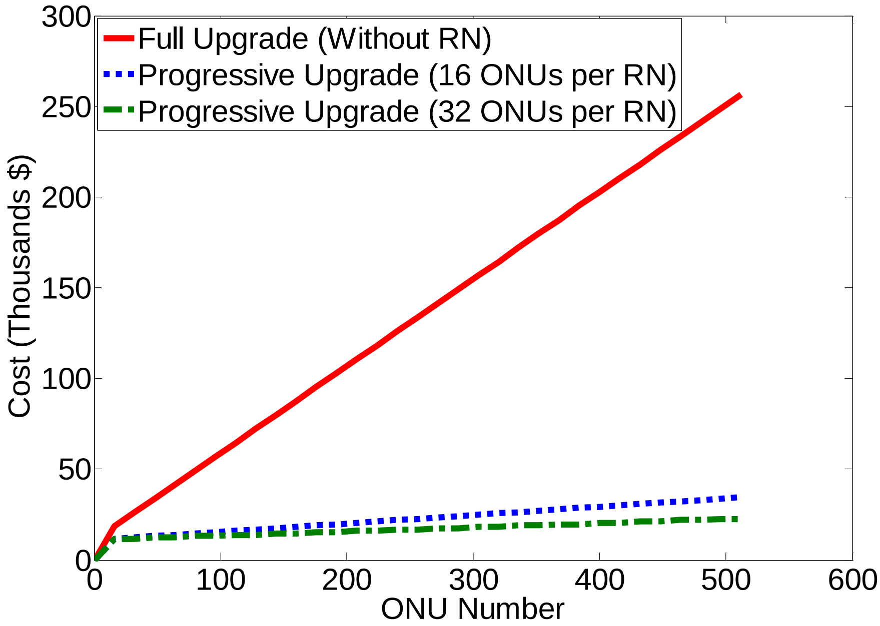

Fig. 7.7: Upgrade costs comparison for 10 Gb/s downstream rate between full upgrade on all ONUs and active RN upgrade (Two proposals of 16 ONUs per RN and 32 ONUs per RN progressive upgrades are demonstrated).

Traffic Load	Downstream Data Rate per ONU (Mb/s)	
	EPON with RN	Full Upgrade
0.1	6.34	6.25
0.2	12.44	12.50
0.3	18.33	18.75
0.4	24.42	25.00
0.5	30.10	31.25
0.6	36.89	37.40
0.7	43.37	43.75
0.8	48.97	50.00
0.9	54.58	56.25

Fig. 7.8: Simulation results showing equal downstream data rate per ONU can be achieved while EPON with active RN architecture having low initial cost upgrade advantage for 160 ONUs equally allocated to 10 RNs.

7.5. Conclusion

The chapter presented a cost effective scheme for 10/1 Gb/s asymmetric EPON upgrade using the active RN with layer two filtering function. Full upgrade on all ONUs' ports to support 10 Gb/s transmission rate are costly and has lower efficiency on utilising the ONU's upgraded port in a large scale EPON system since full link capacity of 10 Gb/s is shared among a large number of ONUs such as 128, 256, and 512. The proposed active RN listens to all incoming frames' headers to gather layer two (or MAC) network information and forms an information table containing MAC and LLID addresses attached to the upstream and downstream ports. This information table is used to filter frames from receiving 10 Gb/s port and forward frames downstream to the ONUs at a transmission rate of 1 Gb/s. The advantage of such a scheme is to upgrade only the feeder link between the OLT and active RNs while the large number of ONUs' transceivers remains at 1 Gb/s, which significantly reduces the upgrade capital spent and also the unit cost for customer.

The simulation results showed an equal downstream data rate can be achieved for both EPON with active RN upgrade and full upgrade. Furthermore, upgrading small amount of active RNs (for an example of 10) results in a much cheaper cost compared to upgrading all ONUs (in hundreds). From the cost analysis in section 7.4, an estimated initial upgrade cost of approximately $87,600 is required for full upgrade while EPON with active RN architecture only requires an upgrade cost of approximately $18,200 under the condition of same downstream data rate per ONU for EPON with active RN architecture and full upgrade (160 ONUs). Therefore, the proposed EPON with active RN architecture appears to be an attractive solution for SPs to migrate from traditional 1G-EPON to 10G-EPON and at the same time increase the ROI by reducing the initial capital expenditure.

7.6. References

[1] G. Kramer, "10G-EPON: Drivers, Challenges and Solutions," in *Proc. 35th European Conference on Optical Communication*, 2009.

[2] G. Kramer, "What is Next for Ethernet PON?," in *Proc. 5th International Conference on Optical Internet and Next Generation Network*, pp. 49-54, Jul. 2006.

[3] G. Kramer, "Ethernet Passive Optical Networks," *McGraw-Hill Professional*, 2004, ISBN: 0071445625.

[4] IEEE 802.3 ah EFM standard, (part of IEEE standard 802.3).

[5] G. Kramer, G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," *IEEE Commun. Mag*. vol. 40, no. 2, pp. 66-73, Feb. 2002.

[6] M. Hajduczenia, H. J. A. da Silva, P. p. Monteiro, "Development of 10 Gb/s EPON in IEEE 802.3av," *IEEE Commun. Mag.*, vol 46, no. 7, pp. 40-47, July 2008.

[7] R. Lin, "Next Generation PON in Emerging Networks," in *Proc. Optical Fiber Communication Conference*, pp. 1-3, Feb. 2008.

[8] IEEE P802.3 av task force, available online http://www.ieee802.org/3/av/

[9] M. Hajduczania, H. J. A. da Silva, "Next generation PON systems – Current status," in *Proc. 11th International Conference on Transparent Optical Networks*, pp. 1-8, Jun. 2009.

[10] C. Chen, Z. Chair, B. Velmurugan, "10G EPON: Next generation Ethernet passive optical networks," in *Proc. Optical Fiber Communication Conference*, Mar. 2009.

[11] M. Hajduczenia, H. J. A. da Silva, N. Borges, "Discovery Process for Emerging 10 Gb/s EPONs," *IEEE Commun. Mag.*, vol 46, no 11, pp. 82-90, November 2008.

[12] J. Prat, "Next-Generation FTTH Passive Optical Networks: Research towards unlimited bandwidth access," *Springer*, 2008, ISBN: 9781402084690.

[13] K. Tanaka, "Coexistence with Current Systems – 10GE-PON System Configuration," electronic report, available at:
http://www.ieee802.org/3/av/public/2007_03/3av_0703_tanaka_1.pdf

[14] F. Effenberger, "10G EPON downstream:1590 nm is the right choice," electronic report available at:
http://www.ieee802.org/3/av/public/2007_11/3av_0711_effenberger_2.pdf

[15] G. Kramer, "10G EPON – 1G EPON Coexistence," electronic report available at:
http://www.ieee802.org/3/av/public/2007_01/3av_0701_kramer_1.pdf

[16] Tran, A. V., Chae, C. –J., Tucker, R. S., "Low-cost and scalable passive optical network architecture using remote repeater," *IEE Electron. Lett.*, vol. 42, no. 10, pp. 589-591, May 2006.

[17] C. A. Chan, M. Attygalle, A. Nirmalathas, "Active Remote Node with Layer Two Forwarding for Improving Performance of EPON", in *Proc. IEEE Conference on Global Telecommunications*, pp. 1-5, 2008.

[18] C. A. Chan, M. Attygalle, A. Nirmalathas, "Local traffic prediction-based bandwidth allocation scheme in EPON with active forwarding remote repeater node," in *Proc. 14th OptoElectronics and Communications Conference*, pp. 1-2, Jul. 2009.

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

[20] A. V. Tran, C.-J., Chae, R. S. Tucker, "Ethernet PON or WDM PON: A Comparison of Cost and Reliability," in *Proc. IEEE International. Region 10 Conference*, pp. 1-6, Nov. 2005.

8 Conclusions and Future Works

8.1. Thesis Overview

This thesis investigated architectures and techniques for improving the performances of optical access network implementations based on both wavelength division multiplexed passive optical network (WDM-PON) and time division multiplexed PON (TDM-PON) systems. Its aims were to seek several feasible solutions to a number of emerging service requirements such as independent service provisioning in WDM-PON, local traffic quality of service (QoS) in EPON, downstream bandwidth enhancement in large scale optical access network, upstream dynamic bandwidth assignment (DBA) scheme in EPON and the evaluation of 10 Gb/s EPON system upgrade options. The summary of the technical chapters presented in this thesis is as follows.

Chapter 3 investigates the issue of independent services provisioning in WDM-PON. A simple technique of closely separated baseband channels generation and separation is experimentally demonstrated to prove the feasibility for practical deployment. This proposed scheme uses a single laser and modulator to generate two data stream channels, one at baseband and the other at a low frequency subcarrier sideband respectively using amplitude-shift keying (ASK) signal. The two data streams are independent and can be provided by different service providers (SPs). At the customer premise’s receiver side, an optical delay interferometer (differential phase-shift keying (DPSK) demodulator) is used to optically separate the two independent data channels and standard baseband receivers are used for detection. This scheme has been experimentally demonstrated using two independent 1.5 Gb/s data streams. Also, in this chapter, the crosstalk effect of subcarrier multiplexing technique is discussed. Through experiment and simulation, optimum bias drive amplitude region in biasing the Mach-Zehnder modulator (MZM) and the different value of radio frequency (RF) signal amplitude for the subcarrier channel have been analysed to obtain a balanced result for both channels.

Chapter 4 presents a discussion of the limitation of existing EPON standard in delivering inter-ONU communications traffic. According to logical topology emulation (LTE) technique defined in the EPON standard [1-3], inter-ONU traffic are required to go through the distribution link upstream and then downstream (due to directivity of passive splitter/combiner), which results inefficient use of EPON bandwidth. In this chapter, a remote repeater node (RN) incorporating active layer two forwarding function is proposed to be used in EPON architecture. The active RN, which locates after the first split point listens to all incoming EPON frames from upstream and downstream to gather layer two or medium access control (MAC) information for all devices that are connecting to it and form a forwarding table containing MAC and logical link identity (LLID) addresses. Using this forwarding table, the active RN is capable of filtering frames and redirecting local intra-subnet frames. The motivation of the proposed architecture is to design an improved EPON system. Therefore, the proposed use of the active RN will have no impact on existing EPON protocols such as Multipoint Control Protocol (MPCP) and DBA machine and no modification needed on existing OLT and ONU. The simulation results in this chapter have proved significant performance increases in a symmetric 1 Gb/s EPON with active RN architecture in terms of local intra-subnet traffic and downstream traffic latencies.

Chapter 5 describes the issue of unable to deliver high quality broadband service to large scale network due to bandwidth bottleneck at the EPON downstream. When the number of users increases, the available downstream data rate per user is also decreased in the shared PON system. The use of EPON incorporating active RN with layer two forwarding function has been discussed in Chapter 4. Therefore, the benefits of such architecture are extended in this chapter. Due to the major functions of filtering unwanted frames and redirecting local intra-subnet frames at the active RN, this proposed architecture results a large portion of free downstream bandwidth (previously used to redirect local inter-ONU traffic at the OLT in conventional EPON system) can be used to accommodate more external traffic. Therefore, simulation and theoretical analysis have been carried out to demonstrate a significant amount of downstream bandwidth can be improved; and alternatively the number of customers can be increased while keeping same data rate compared to conventional EPON system for the advantage of scalability.

In Chapters 4 and 5, static bandwidth assignment (SBA) method is used in the simulations due to the reason that the objectives of the two chapters are to demonstrate the basic functions and benefits of the proposed architecture. However, the limitation of SBA method has been discussed in Chapter 6. If SBA scheme is used, the OLT will allocate same timeslots to all ONUs although some ONUs' buffers are empty while some ONUs will have large amount of traffic to be sent due to the burstiness of Ethernet traffic, which directly decrease the network efficiency. Therefore, Chapter 6 investigates the current important issues of fair and efficient upstream bandwidth assignment schemes in EPON. A simple novel DBA mechanism named local traffic prediction-based DBA (LT-DBA) is proposed to enable upstream data rate improvement per customer. The LT-DBA mechanism uses excess granting of timeslot for ONUs, which contain local intra-subnet traffic (since this traffic will be redirected at the active RN). However, due to random traffic is generated by the end users, collision avoidance techniques at the access and feeder links are required and were proposed in the chapter. The simulation of LT-DBA algorithm in EPON incorporating active RN architecture has demonstrated large improvements in several performance parameters including average packet delay, frame loss ratio, average queue size in ONU as well as upstream and downstream data rate per ONU compared to conventional EPON system.

Chapter 7 presents a discussion of issues in 10 Gb/s EPON upgrade compatibility with existing 1 Gb/s EPON and modifications on the protocol. Full upgrade on all ONU's transceiver ports to support 10 Gb/s transmission rate are costly and has lower efficiency on utilising the bandwidth since the link capacity is shared among a large number of ONUs. The EPON incorporating active RN with layer two forwarding architecture described in Chapters 4 and 5 has the initial cost advantage on upgrading the existing 1 Gb/s EPON system to asymmetric 10 Gb/s downstream/1 Gb/s upstream system. The main advantage of such a scheme is to upgrade only the feeder link between the OLT and the active RNs while remains a large number of ONUs' transceivers at conventional 1 Gb/s, which significantly reduces the upgrade capital spent and also the unit cost for customers. A simulation has been conducted to show an equal downstream data rate can be achieved for both EPON with active RN upgrade compared to full upgrade on all ONUs. As a result, the proposed EPON with active RN architecture appears to be an attractive solution not only on improving the upstream and downstream performance in existing 1G-EPON system but also capable of increasing the number of users and easy for upgrading to 10 Gb/s system while keeping a low initial upgrade cost for SPs.

8.2. Directions for Future Work

In the previous chapters in the thesis, intensive simulations and theoretical analysis have been demonstrated to examine the feasibility of the EPON with active RN architecture. Although the proposed architecture has been proved to provide many advantages compared to conventional EPON system, several research topics were identified as an extension to further improve the architecture as shown below.

8.2.1. Intra and inter ONU scheduling in EPON with active RN

In Chapter 6, the performance of a packet-based network can be characterised by several parameters such as bandwidth, packet delay, delay variation and packet loss ratio. An efficient and fair access network system maintains the QoS, which refers to a network's ability to provide all the mentioned parameters on a per-connection or per-session basis. However, not all networks can maintain a per-connection state quality assurance [1]. Therefore, in order to support different applications and services' requirements, a network can separate all the incoming traffic into a limited number of classes and provide differentiated service for each class to maintain the class of service (CoS) [1].

The simulation built in Chapter 6 aims to test the feasibility of the LT-DBA algorithm in comparison to standard DBA and fixed service SBA methods. All incoming traffic into an ONU from the customer sites are handled in one class (which means equal priority for all packets). However, a real access network consists of multi-services or applications with different requirements. Variable-bit-rate (VBR) video streams are highly burst and require a delay of less than 100 ms [2, 3]; constant-bit-rate (CBR) streams for legacy equipment such as plain old telephone service lines requires minimum delay of 10 ms and hence maximum jitter [2, 3]; while best-effort (BE) traffic requires minimum QoS but represents a major amount of network usage. Without CoS differentiation, video calls will experience similar priority as BE traffic, which is not desired. In order to maintain the CoS differentiation mechanism, inter-ONU and intra-ONU scheduling mechanisms as shown in Fig. 8.1 can be implemented in the ONU to provide QoS to EPON incorporating active RN architecture. As a consequence, an extended simulation model can be performed to evaluate the effects of intra-ONU and inter-ONU scheduling mechanisms to the LT-DBA method.

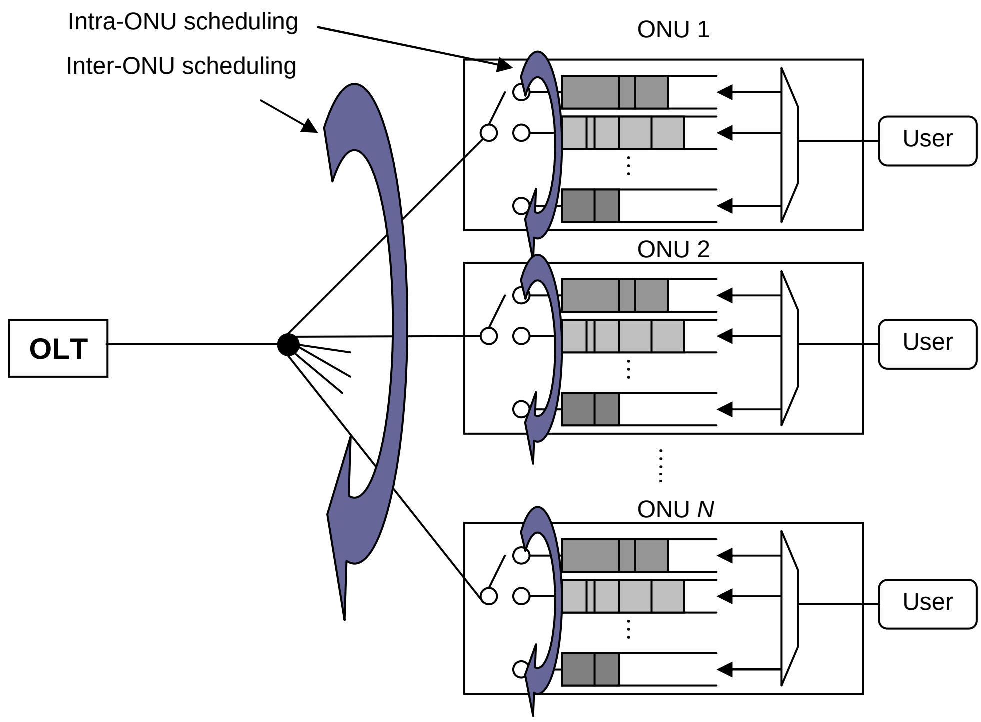

Fig. 8.1: Intra-ONU and inter-ONU scheduling [1].

8.2.2. Advanced DBA for differentiated class of service

As defined in IEEE 802.1p, traffic classes can be mapped into seven priority queues [2]. Less priority queues can be implemented where two or more traffic classes can be grouped together to share the same priority. Although the differentiation of CoS in EPON make the network an efficiency access system to support triple play services, common issues such as light-load penalty and Ethernet packet pre-emption can occur. In contrast to the inter-ONU scheduling methods in previous section, the awareness of CoS can be implemented in the OLT's bandwidth assignment agent.

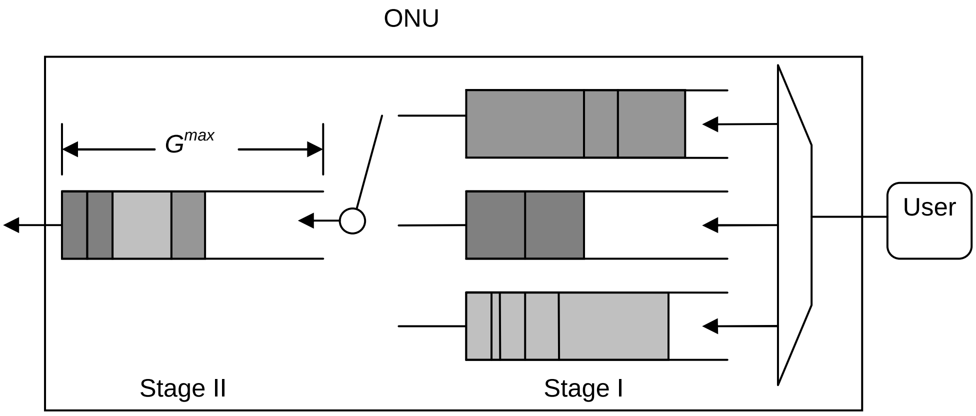

Fig. 8.2: Tandem queue in ONU [4].

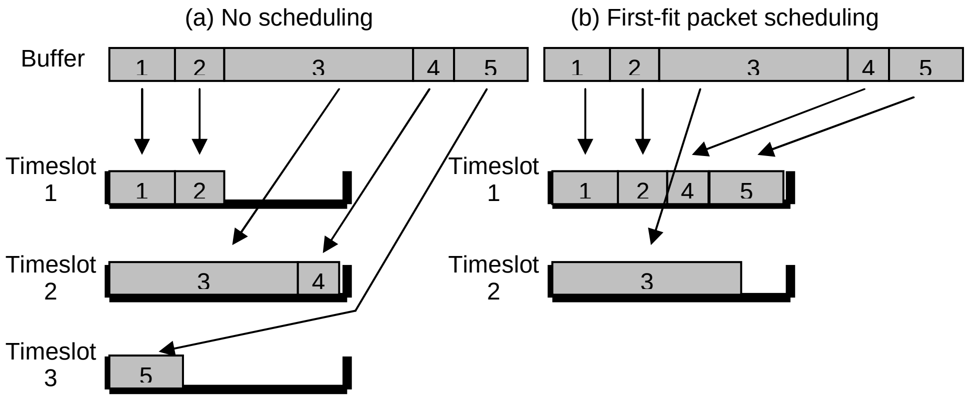

Fig. 8.3: Packet scheduling in ONU [9].

At low traffic load where the OLT is able to grant an ONU of its requested slot size, more packets will arrive to the ONU with higher priority during the wait time of receiving the REPORT message and the start of slot transmission time. Due to the implementation of CoS differentiation, these newly arrived higher priority packets will be sent and some lower-priority packets are pre-empted and left in the queue. This scenario may repeat for several transmission cycles and increase the network efficiency penalty. However, as the load increases, the lower priority queues grow faster and the light-load penalty decreases. Several techniques have been developed to address this issue such as tandem queuing and CBR credit method [1]. Furthermore, the newly arrived higher priority packets might not have the same packet size as the reported lower-priority packet. This will prevent the transmission of the newly arrived higher-priority packets and create unused slot remainder. Since the IEEE 802.3 standard does not allow Ethernet packets fragmentation [2, 4], packet pre-emption will result in an under-utilised slot unless the newly arrived higher-priority packets have the same combined size as a pre-empted lower-priority packet, which is rare [5]. As a consequence, this issue has been studied by researchers and several scheduling methods have been proposed [6-8]. Among the different scheduling methods [4, 6-9], solutions such as tandem queuing and packet scheduling can be implemented in the ONUs and active RN as shown in Fig. 8.2 and Fig. 8.3 [4, 9] to further improve the LT-DBA performance.

Differentiation of CoS can be extended into LT-DBA algorithm to improve the EPON with active forwarding RN in supporting prioritised traffic and application in order to provide better QoS to real-time services. Bridging function in the ONU or devices connecting the ONU provides the forwarding decision of sending the local traffic frame to the OLT. A special queue (non-priority queue) can be allocated specially for all local traffic frames and the amount of this buffer can be known to the OLT through the REPORT message. Once the OLT has the knowledge on how much local traffic an ONU has, it can better allocate excess timeslot rather than relying on prediction technique regarding the amount of free timeslot occurred due to local traffic redirection at the active RN in the previous transmission cycle. Furthermore, the ONU can provide efficient packet scheduling method since the excess timeslot size will be stated in a different Grant start and length as discussed in section 6.3.2 in Chapter 6. All frames that is needed to be transmitted to the OLT will be scheduled to send in the timeslot determined by standard DBA method while the local traffic frames that will be redirected at the active RN will be scheduled to be transmitted in the excess timeslot. This scheduling method can greatly reduce jittering in the active RN’s upstream scheduler. However, to complete the above extension, a more advanced simulation model with ONUs to support multiple CoS has to be built. As a consequence, it is an exciting follow up research topic on extending the LT-DBA algorithm to support differentiated CoS in EPON with active forwarding RN to support triple-play services.

8.2.3. Active filtering and forwarding RN chipset

In Chapters 4, 5 and 6, discrete event simulation model and self-similar traffic generation are used for both upstream and downstream to generate Ethernet packets. However, the proposed architecture of EPON with active RN can be further tested using real traffic from services such as Internet protocol TV (IPTV), high-definition TV (HDTV) and peer-to-peer (P2P). In order to perform this experiment, a chipset containing full forwarding and filtering functions of the active RN can be built. Several application specific chipsets have been developed by researchers [10-12] for EPON system. Therefore, chipset developing to simulate the real video traffic in order to evaluate the QoS performance for the proposed architecture is another interesting future work.

8.2.4. Symmetric 10 Gb/s EPON using active RN

In Chapter 7, an asymmetric 10G downstream/1G upstream EPON architecture is proposed using active filtering RN. This architecture provides a low cost upgrade option for service providers due to the reason that only transceiver ports upgrade is required between the OLT and the active RNs while a large number of ONUs will remain in 1 Gb/s transmission rate. The simulation shown in the chapter is only capable of demonstrating the asymmetric 10G downstream/1G upstream system. However, multiplexing technique can be implemented in the active RN to multiplex several 1 Gb/s upstream data streams (from the ONUs to the active RNs) into 10Gb/s link rate between OLT and active RNs to achieve symmetric 10G-EPON with active RN architecture. This architecture will provide a boost in upstream bandwidth for customers by keeping the 1 Gb/s ONUs.

8.2.5. Multicast support in 10 Gb/s EPON

As described early in the thesis, bandwidth demand in the access network is increasing dramatically. High bandwidth demand applications such as IPTV and HDTV have begun to attract many customers. Most of these applications use multicast technique to transmit video streams to the end users. According to IEEE 802.3av Task Force group, the 10 Gb/s EPON will be using separate wavelength channels to deliver 10 Gb/s and 1 Gb/s data streams [13]. If a multicast stream were always broadcast onto both downstream channels, significant amount of bandwidth will be wasted and the 1 Gb/s downstream can be easily saturated [14]. Therefore, the OLT must be implemented with additional function such as LLID based multicast forwarding database in order decide which logical channel in downstream a particular multicast stream should be forwarded. This issue has created an interesting research topic in providing multicast traffic in next generation EPON. If an EPON with active filtering

RN architecture is used, the complication of the multicast issue is reduced since only one wavelength channel is used between the OLT and active RN. However, specific function to replicate and filter multicast streams in the active RN will further improve the efficiency of the proposed architecture.

8.3. Conclusions

This thesis presents a detailed study of specific techniques and architectures aimed at achieving improved performance of the access network while meeting emerging service requirements such as independent services provisioning in WDM-PON, upstream and downstream performance enhancement in EPON as well as the evaluation of the next generation EPON upgrade. During this study, a detailed understanding of current access and broadband networks infrastructure has been gained. Furthermore, novel architectures and technologies have been proposed and demonstrated through experiments and simulations to verify the feasibility towards practical implementation. Moreover, the research has identified further research that is essential towards the development of a cost-effective next generation optical access network infrastructure supporting QoS framework and services that exploit QoS differentiation.

8.4. References

[1] G. Kramer and G. Pesavento, "Ethernet Passive Optical Network (EPON): Building a Next-Generation Optical Access Network," *IEEE Commun. Mag.*, vol. 40, Feb. 2002, pp. 66-73.

[2] IEEE 802.3ah EFM, http://www.ieee802.org/3/efm/.

[3] G. Kramer, *Ethernet Passive Optical Networks*, McGraw-Hill Prof., ISBN:0071445625.

[4] G. Kramer, "Ethernet Passive Optical Networks," *McGraw-Hill Prof*., 2004, ISBN: 0071445625, Chapter 16, pp. 215-236.

[5] B. Mukherjee, "Optical WDM networks," *Springer*, ISBN: 0387290559, chapter 5.

[6] M. R. Radivojevic, P. S. Matavulj, "Implementation of Intra-ONU Scheduling for Quality of Service Support in Ethernet Passive Optical Networks," *J. Lightwave Tech*. vol. 27, no. 18, pp. 4055-4062, Sept. 2009.

[7] G. Kramer, A. Banerjee, N. K. Singhal, B. Mukherjee, S. Dixit, Y. Ye, "Fair queuing with envelopes (FQSE): a cousin-fair hierarchical scheduler for subscriber access networks," *IEEE J. Sel. Areas in Commun*., vol. 22, no. 8, pp. 1497 – 1513, Oct. 2004.

[8] N. Ghani, A. Shami, C. Assi, M. Y. A. Raja, "Intra-ONU bandwidth scheduling in Ethernet passive optical networks," *IEEE Commun. Lett*., vol 8, no. 11, pp. 683-685, Nov. 2004.

[9] G. Kramer, "Ethernet Passive Optical Networks," *McGraw-Hill Prof*., 2004, ISBN: 0071445625, Chapter 14, pp. 189-200.

[10] C. Kim, T.-W. Yoo, Y. Kwon, B.-T. Kim, "Design and Implementation of an EPON Master Bridge Function in an ASIC," in *Proc. 11h IEEE Symposium Computer and Communication*, pp. 572-577, Jun. 2006.

[11] K.-S. Han, K.-O. Kim, T. W. Yoo, Y. Kwon, "The design and implementation of MAC security in EPON," in *Proc. 8th International Conference on Advanced Communication Technology*, pp. 1673-1676, Feb. 2006.

[12] H. Chen, L. Su, D. Jin, L. Zeng, "Design of application specific chip for EPON," in *Proc. 5th International Conference ASIC*, pp. 865-869, vol. 2, Oct. 2003.

[13] IEEE P802.3 av task force, available online http://www.ieee802.org/3/av/

[14] C. Chen, Z. Chair, B. Velmurugan, "10G EPON: Next generation Ethernet passive optical networks," in *Proc. Optical Fiber Communication Conference*, Mar. 2009.

Appendix A: Acronyms

	2R	re-amplification, reshaping
	3R	re-amplification, reshaping and retiming
A		
	ACTS	Advanced Communications and Technologies and Services
	ADSL	asymmetric digital subscriber line
	AON	active optical network
	ASE	amplified spontaneous emission
	ASK	amplitude shifted keying
	AT&T	American Telephone & Telegraph
	ATM	asynchronous transfer mode
	ATM-PON	asynchronous transfer mode passive optical network
	AWG	arrayed waveguide grating
B		
	BE	best-effort
	BER	bit-error-rate
	BPON	broadband passive optical network
C		
	CBR	constant-bit-rate
	CDR	clock and data recovery
	CO	central office
	CoS	class of service
	CRC	cyclic redundancy check
	CSMA/CD	carrier-senses multiple access with collision avoidance
	CSR	carrier-to-subcarrier ratio

D

DA	destination address
DBA	dynamic bandwidth assignment
DFB LD	distributed feedback laser diode
DI	delay interferometer
DPSK	differential phase-shift keying
DVD	digital versatile disc
DWDM	dense wavelength division multiplexing

E

EDC	electronic dispersion compensation
EDFA	Erbium-doped fibre amplifier
EFM	Ethernet in the First Mile
EPON	Ethernet passive optical network

F

FBG	fibre brag gating
FEC	forward error correction
FFP	fibre Fabry Perot
FIFO	first-in-first-out
Fig	figure
FSAN	Full Service Access Network
FSR	free-spectral-range
FTTB	fibre-to-the-building
FTTC	fibre to the curb
FTTH	fibre-to-the-home
FTTP	Fibre-to-the-premise

G

G	Giga
Gb/s	Gigabit per second
GFP	Generic Framing Procedure
GMII	gigabit media independent interface
GPON	gigabit PON

H

HDTV	high definition TV

HFC	Hybrid Fibre/Coaxial
Hz	Hertz

I

IEEE	Institute of Electrical and Electronics Engineers
IGMP	Internet group management protocol
IP	Internet protocol
IPACT	interleaved polling algorithm with adaptive cycle time
IPTV	Internet protocol television
ISDN	integrated services digital network
ITU	International Telecommunication Union

K

KDDI	Kokusai Denshin Denwa International
km	kilometre

L

LAN	local area network
LED	light emitting diode
$LiNbO_3$	Lithium Niobate
LLID	logical link identity
LN-MOD	Lithium Niobate modulator
LTE	logical topology emulation

M

M	Mega
MAC	medium access control
Mb/s	Megabit per second
MPCP	multi-point control protocol
MZIWC	Mach-Zehnder interferometer wavelength converter
MZM	Mach-Zehnder Modulator

N

NICTA	National Information and Communication Technology Australia
NZN	non-return zero

O

OBP	optical bandpass filter

OC	optical circulator
OCSS	optical carrier suppression and separation
ODN	optical distribution network
OLT	optical line terminal
ONU	optical network unit
ORU	optical repeater unit
OSI	Open System Interconnection
OTDR	optical time-domain reflectometer

P

P2P	peer-to-peer
PCM	pulse-code-modulation
PIEMAN	photonic integrated extended metro and access network
PON	passive optical network
POTS	plain old telephone system
PRBS	pseudorandom binary sequence
PTP	point-to-point
PTPE	Point-to-point Emulation

Q

QoS	quality of service
QPSK	quadrature phase-shift keying

R

RF	radio frequency
RN	remote node
ROI	return on investment
RS	Reed-Solomon
RTT	Round trip time

S

SA	source address
SBA	static bandwidth assignment
SC	star coupler
SCB	single-copy broadcast
SDTV	standard definition television
SLA	service level agreements

SME	shared-medium emulation
SMF	single mode fibre
SOA	semiconductor optical amplifier
SP	service provider

T

T1	trunk level 1
TDM	time division multiplexing
TDMA	time division multiple access
TDM-PON	time division multiplexed passive optical network

V

VBR	variable-bit-rate
VCSEL	vertical cavity surface emitting laser
VDSL	very high speed digital subscriber line
VOD	video-on-demand

W

WDM-PON	wavelength division multiplexed passive optical networks

-200-

Appendix B: Publications

1. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, "Generation and Separation of Closely Separated Dual Baseband Channels for Provisioning of Independent Services in WDM-PON," *IEEE Photon. Tech. Lett.*, vol. 19, no. 16, pp. 1215 – 1217, Aug. 2007

2. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, "Remote Repeater based EPON with MAC Forwarding for Long Reach and High-Split Ratio Passive Optical Networks," *J. Optical Commun. and Networking*, vol. 2, no. 1, pp. 28-37, Jan. 2010.

3. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, "A Local Traffic Prediction-based Dynamic Bandwidth Assignment Scheme for EPON Incorporating Active Filtering Remote Repeater Node," To be submitted.

4. Manik Attygalle, Chien Aun Chan, Thas Nirmalathas, "Closely Separated Dual Baseband Channel Generation and Separation for Provision of Broadcast Traffic in WDM-Passive Optical Networks," in *Proc. Australian Conference on Optical Fibre Technology, Melbourne, Australia,* Dec. 2006.

5. Chien Aun Chan, Manik Attygalle, Thas Nirmalathas, "Provision of Independent Services in WDM-Passive Optical Networks using Closely Separated Dual Baseband Channels," in *Proc. Optical Fibre Communication Conference*, paper JWA48, Anaheim, USA, Mar. 2007.

6. M. Attygalle, C. A, Chan, and A. Nirmalathas, “Optimisation of Drive Amplitude and Stability Analysis for Dual Baseband Channel Generation using a Single Laser and Modulator”, in *Proc. International Conference on the Optical Internet/Australian Conference on Optical Fibre Technology*, paper WeA2.3, Melbourne, Australia, Jun. 2007.

7. C. A, Chan, M. Attygalle, T. Nirmalathas, “Improving Network Performance Using Active Remote Node In EPON,” in *Proc. Opto Electronics and Communications Conference/Australian Conference on Optical Fibre Technology,* paper Thp-73, Sydney, Australia, Jul. 2008,.

8. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, “Active Remote node with Layer Two Forwarding For Improving Performance of EPON”, in *Proc. IEEE Global Communication*, *New Orleans*, *USA*, Dec. 2008.

9. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, “Local Traffic Prediction-based Bandwidth Allocation Scheme in EPON with Active Forwarding Remote Repeater Node,” in *Proc. 14th Opto Electronics and Communications Conference*, Hong Kong, Jul. 2009.

10. Chien Aun Chan, Manik Attygalle, Ampalavanapillai Nirmalathas, “Evaluation on 10/1 Gb/s Asymmetric EPON with Active Filtering Remote Node Design and Modelling,” in *Proc. Optical Network Design and Modelling Conference*, Japan, Feb. 2010.