

Dynamic Bandwidth Allocation MAC Protocols for Gigabit-capable Passive Optical Networks

Ching-Hung Chang

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Abstract

The research initiatives addressed in this thesis are geared towards improving the performance of passive optical networks (PONs) through the development of advanced dynamic bandwidth allocation (DBA) protocols. In particular, the aim of the research undertaken is to enhance the quality of service (QoS) offered by standard PONs by means of providing subscribers with service level agreement (SLA) to fulfil applications and associated bandwidth requirements on demand.

To accomplish the research objectives, a novel service and bandwidth focused DBA protocol is developed for standard time division multiplexing (TDM), gigabit-capable PONs (GPONs) by flexibly assigning a guaranteed minimum bandwidth to each optical network unit (ONU), terminated at subscribers premises. Modelling and simulation of the developed algorithms have displayed a tenfold enhancement in network performance, showing a superior performance to other published DBA protocols, in terms of mean packet delay. To accomplish protocol optimisation, the ONU upstream transmission properties of TDM-PONs have been further analysed and subsequently the ONU data transfer order in each communication cycle has been dynamically configured to increase the network upstream throughput by overlapping the upstream transmission period with parts of the bandwidth request-allocation process between OLT and ONUs. In addition, with the objective of extending the application of the developed protocol to long-reach PONs by means of reducing the augmented propagation delays due to the network's extensive reach, the concept of virtual communication cycles has been incorporated into the optimised DBA algorithm. This approach demonstrates comparable transmission efficiency in the context of subscriber throughput and packet delay as in a standard PON but at much longer distances from the network exchange.

To overcome the inevitably limited communication capacity of single wavelength TDM protocols and with the transportation of the ever increasing, time-sensitive, multi-media services in mind, a novel multi-wavelength DBA protocol is then developed to be applied to a wavelength division multiplexing-PON. With this protocol, both the downstream and upstream network capacity is dynamically adjusted according to subscribers' service level and bandwidth demand in each polling cycle as opposed to a fixed upstream network capacity in TDM-PONs. It therefore also demonstrates improved upstream transmission efficiency.

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Abbreviations

10GEAPON	10 Gbit/s Ethernet passive optical network
AF	Assured forwarding
ADMB	Advanced dynamic minimum bandwidth
ADSL	Asymmetric digital subscriber line
APON	ATM-passive optical network
ATM	Asynchronous transfer mode
AWG	Arrayed waveguide grating
BE	Best effort
BPON	Broadband passive optical network
BS	Antenna base station
CAPEX	Capital expenditures
CDMA	Code division multiple access
CO	Centre office
CoS	Class of service
CPE	Current processing environment
CW	Continuous waves
CWDM	Coarse WDM
DBA	Dynamic bandwidth allocation
DBRu	Dynamic bandwidth report upstream
DMB	Dynamic minimum bandwidth
DSL	Digital subscriber Line
DWDM	Dense WDM
EDFA	Erbium-doped fibre amplifier
EF	Expedited forwarding
FEC	Forward error correction
EPON	Ethernet passive optical network
FTTB	Fibre to the building
FTTC	Fibre to the curb
FTTH	Fibre to the home

FSAN	Full service access network
GEM	GPON encapsulation method
GPON	Gigabit-capable passive optical network
HDTV	High definition television
IEEE	Institute of electrical and electronics engineers
IP	Internet protocol
IPACT	Interleaved polling with adaptive cycle time
ISP	Internet service provider
ITU-T	International telecommunication union - telecommunication standardization
MAC	Medium access control
MDMB	Multi-wavelength dynamic minimum bandwidth
MPCP	Multi-point control protocol
OAM	Administration and maintenance
OLT	Optical line terminal
ONT	Optical network terminal
ONU	Optical network unit
OPEX	Operational expenditures
P2MP	Point-to-multi-point
P2P	Point-to-point
PCBd	Physical control block downstream
PDC	Perfect difference code
PLI	Payload length indicator,
PLOu	Physical layer overhead upstream
PLOAMu	Physical layer operations administration and maintenance upstream
PTI	Payload type indicator
PON	Passive optical networks
QoS	Quality of service
RN	Remote node
RSOA	Reflective semiconductor optical amplifier
RTT	Signal round trip time

SLA	Service level agreement
TDM	Time division multiplexing
TL	Tunable laser
TSD	Two-state dynamic minimum bandwidth
VDSL	Very-high-bit-rate DSL
VoD	Video on demand
VOIP	Voice-over-IP
WDM	Wavelength division multiple

Chapter 1

Introduction

This chapter starts with an overview of the developments in access networks, naturally moving on to concentrate on passive optical network architectures and standards. Consequently the research drive and apparent contribution of the undertaken research in gigabit-capable passive optical networks (GPONs), long-reach PONs and multi-wavelength PONs are analytically presented to be proceeded by the outline of the thesis.

1.1 *Overview of Access Networks*

As shown in Figure 1-1, an access network can be utilised to deliver video, voice or data services over copper cables, optical fibres, wireless links or a combination of primarily copper and fibre [1]. Depending on the application, the remote node that connects the last mile with the feeder medium can be either active or passive employed to aggregate and distribute data between subscribers and the local exchange. The local exchange, that is often also referred to as the central office (CO) is the gateway to the metropolitan network whereby all COs, within a city or large region are typically connected in the form of a fibre optical based ring topology that spans over tens to hundreds of kilometres for the delivery of multi-media services from service providers to customers. At the end of the chain, the metropolitan network is terminated at a core network router, interconnecting cities or extended regions over distances of hundreds to thousands of kilometres in a mesh topology [2].

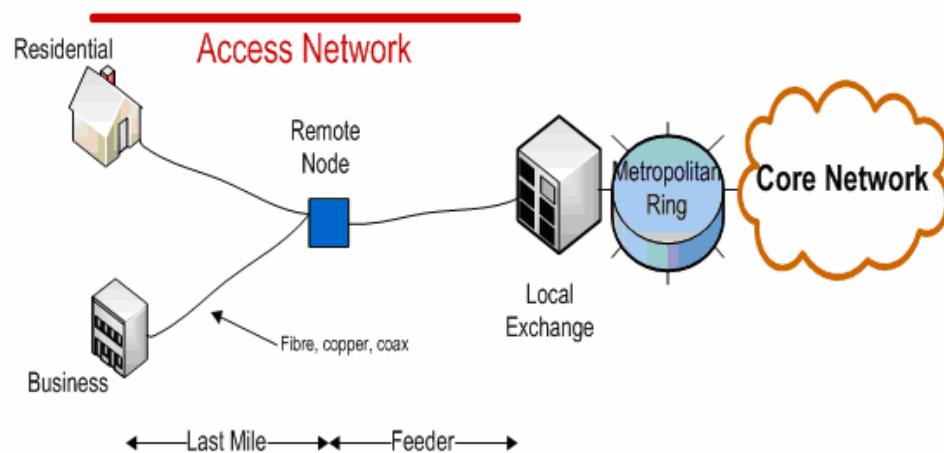


Figure 1-1 A model of the access, metropolitan and core networks

The current access network technologies in rapid development include wireless and wireline alternatives with the former typically deployed in point to multipoint (P2MP) network topologies to provide broadband connectivity [3]. WiMAX [4] and WiFi [5], in particular, could offer 70 Mbit/s connections for distances of 5 km and 50 Mbit/s connection for up to 100 meters respectively. Nevertheless, they are currently not viable to support high-speed internet and media-rich video applications since the practical bandwidth available is shared among tens to hundreds of users and there are only a few new products developed to incorporate WiMAX [3, 6]. Alternatively, digital subscriber line (DSL) over copper provides another point-to-point access wireline technology option to support each subscriber downstream with up to 24 Mbit/s using its flavour such as asymmetric DSL2plus (ADSL2plus) [7]. However, due to severe noise limitations, especially at high frequencies [3], the effective bandwidth for each subscriber is limited according to the local loop length. For example, to allow subscribers to receive compelling internet and video services at 30 Mbit/s in downstream with 1 Mbit/s upstream capability, local loop length must be decreased to approximately 1000 meters [3]. To expand network reach and accommodate real-time access, the standardisation of the second-generation very-high-bit-rate DSL2 (VDSL2) is regulated in ITU-T G.993.2 [8]. This is achieved by the provision of fat bandwidth pipelines at close proximity to subscribers by replacing the feeder section of the network with optical fibres, resulting to hybrid fibre-copper access

networks capable of providing exceeding 50 Mbit/s data rate in downstream directions [8]. The maximum available bit rate is achieved at a range of about 100 meters [3]. As shown in Figure 1-2, with reference to the fibre-to-the-curb/cabinet (FTTC) architecture, the fibre in VDSL2 applications could be terminated at an optical network unit (ONU), located in a street cabinet, from where twisted pair copper lines extend to the customer premises. The deeper penetration of the fibre all the way to the subscriber is considered as the ultimate technology to meet the ever increasing bandwidth demand, makes it the ideal candidate to meet the capacity challenges in the foreseeable future. Consequently, due to the increasing demand for high-speed access network, fibre-to-the-home (FTTH) architectures have been extensively investigated and standardised [9].

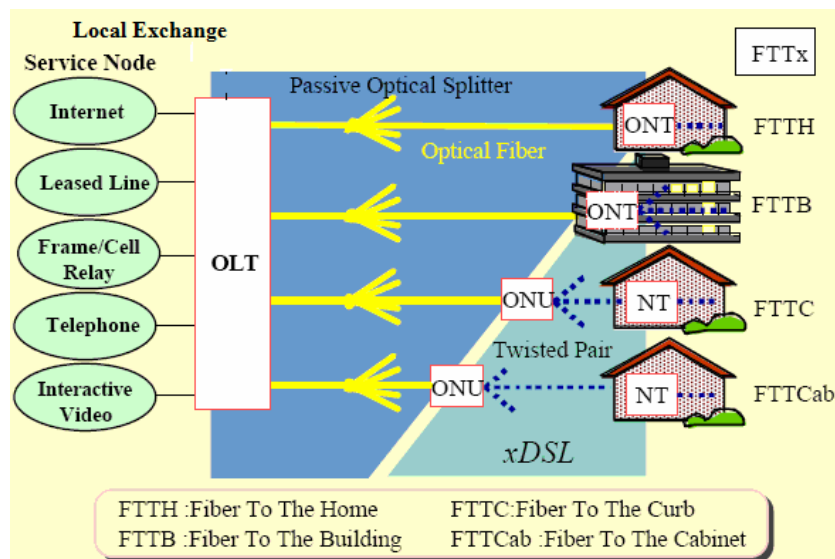


Figure 1-2 Fibre-to-the-X architectures [10]

According to the International Telecommunication Union – Telecommunication Standardization Sector's (ITU-T) full-service access network (FSAN) group [11-13], the advised downstream bandwidth to provide triple-play services for a single residential customer is 73 Mbit/s including three high-definition television (HDTV) channels (3*20 Mbit/s), high-speed internet access (10 Mbit/s), video-conferencing (2 Mbit/s) and telemetric/remote control (1 Mbit/s) [14, 15] as summarised in Table 1-1. Symmetrical bandwidth services in upstream including

online gaming, video-conferencing and education-on-demand in tandem with high-speed internet and other services, are expected to necessitate up to 53 Mbit/s bandwidth [16]. By adding forthcoming services such as remote backup and Web 2.0 applications, the required symmetrical bandwidth for a single residential customer or small business is expected to be increased to up to 100 Mbit/s in the near future [17].

Table 1-1 Bandwidth estimation for a single residential customer [16]

<i>Service</i>	<i>Bandwidth</i>	<i>Comments</i>
Three HDTV channels per residential at 20 Mbit/s each	60 Mbit/s	Three HDTV channels
Education-on-demand, online gaming, internet	10 Mbit/s	Peer-to-peer require symmetrical bandwidth
Video conference of video phone	2 Mbit/s	Requires symmetrical bandwidth
Remote control and sensing	1 Mbit/s	Requires symmetrical bandwidth
Total	73 Mbit/s	Downstream: 73 Mbit/s Upstream: 53 Mbit/s

To meet these capacity challenges in the access network in the foreseeable future, the application of FTTH or the business premises technologies has gained considerable support from incumbents worldwide [2]. In addition, because of the widespread adoption of the Ethernet protocol in local area networks, Ethernet-based FTTH technologies have been extensively investigated and standardised [3, 9]. To start with in Gigabit Ethernet, subscribers access their local exchange at hundreds to thousands Mbit/s via P2P full-duplex fibre connections, with an Ethernet router/switch deployed in a street cabinet. However, placing an active device in the street cabinet would require high operational expenditure (OPEX) due to the need of electrical power provisioning and monitoring as well as maintenance of backup batteries [18]. Furthermore, the network architecture is not

transparent to various signal formats and data rates, and as a result the electronics in the street cabinet would need replacing to support increased data rates or transmission protocols [3]. On the other hand, passive optical network (PON) technologies have rapidly evolved to provide simplicity and extended reach bandwidth in access network architectures by employing passive optical devices in the field such as passive splitters to connect the optical line terminal (OLT) in the local exchange with multiple residential and business customers [3, 19]. Since there is no need to maintain active components operation as well as to avoid malfunctions, PONs is expected to maintain very low OPEX. In addition, by reason of the agnostic nature of the passive splitter, a PON-based access network is optically transparent end to end and capable of supporting various protocols, increasing data rates and additional wavelengths with no alterations in hardware constituting PONs a very practical solution in eliminating the bottleneck in access networks [1, 16, 19-22].

1.2 *Passive Optical Network Standards*

Already standardised PON topologies, including the asynchronous transfer mode (ATM)-PON (APON), Ethernet-PON (EPON), and GPON [3], universally employ time division multiplexing (TDM) as their transmission protocol. Representing the first generation of the PON series, the APON standard was standardized by the ITU-T full-service access network (FSAN) group in the mid-1990s [11-13], to demonstrate end-to-end ATM connectivity based on a point-to-multipoint tree configuration. APON can support up to 32 subscribers at a single upstream data rate, of 155 Mbit/s, and multi-downstream data rates, of 622 or 155 Mbit/s. In order to further explore the potential of optical networking and adapt to Ethernet transmission developments, the Institute of Electrical and Electronics Engineers (IEEE) and ITU-T subsequently defined the EPON and GPON standards respectively. The two provide relatively advanced network performance by increasing the aggregate data rate and the number of supported ONUs. As defined in the IEEE 802.3 family [23, 24], the maximum aggregate

data rate in APON was extended from 622 Mbit/s to 1.244 Gbit/s thereby giving internet service providers (ISPs) more capacity to offer multimedia services in the form of Ethernet packets. In addition, EPONs can support optical distribution network (ODN) classes A and B, which is used to define the relationship between the connection distance and the number of supported ONUs. As shown in Figure 1-3, if the connection distance in EPONs is increased from 10 to 20 km, the number of ONUs will be respectively limited from 32 to 16.

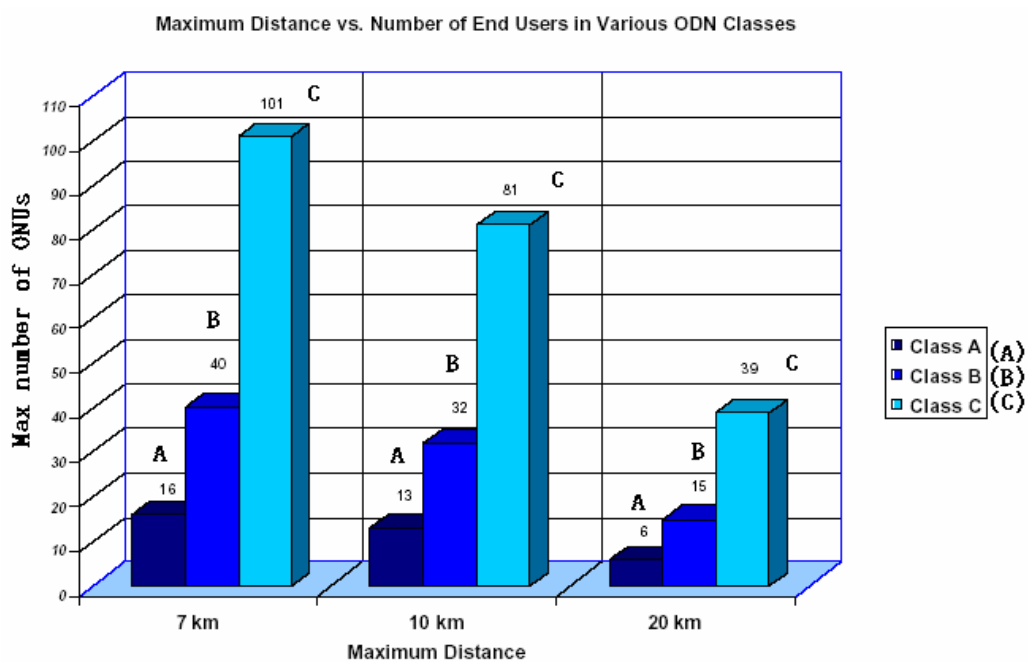


Figure 1-3 The relationship between the maximum distance and the number of end uses in diverse ODN classes [25]

While EPONs can only support 16 ONUs at 20 km connection distances and only fixed aggregate data rates, GPONs defined in ITU-T G.984 family [26-29] display advanced performance in terms of maximum distances, number of ONUs and aggregate data rates. In comparison with EPONs, the maximum achieved distance in GPONs could be increased from 20 km to 60 km with a maximum of 20 km differential reach between ONUs, at a split ratio of 64. In addition, as described in the ITU-T G. 984.2 [27], the upstream and downstream bit rates in GPONs can be set to perform either symmetrical or asymmetrical communication with either 1.244 Gbit/s or 2.488 Gbit/s connections utilised in downstream in contrast to

155 Mbit/s, 622 Mbit/s, 1.244 Gbit/s or 2.488 Gbit/s available in upstream, which drive its widespread adaptation in providing the next generation optical access network [30, 31].

Although not yet standardised research initiatives have concentrated in developing WDM-PON architectures to extend access network capacity beyond the unavoidably limited bandwidth provided by single-wavelength, time-shared and as a result highly congested TDM-PONs. This has been envisaged to be achieved with the demonstration of multiple wavelength operation in both upstream and downstream and consequently sharing the communication medium in the spectrum domain [32-39]. In particular, each ONU will be assigned a unique wavelength to establish communication with the OLT, resulting in logical P2P connections [40-43]. Consequently, network sharing in time will be abolished and total subscriber throughput greatly increased to multiple Gbit/s [32, 41, 44, 45]. In addition, instead of broadcasting downstream data will be directly transmitted only to destination ONUs, providing increased network security [34, 35, 41]

In proposed WDM-PON architectures, both dense WDM (DWDM) and coarse WDM (CWDM) light sources have been considered, according to the ITU-T grid standard [46, 47]. In the former case 50 or 100 GHz spacing, corresponding to 0.4 or 0.8 nm at the operating window of 1500 nm is utilised to flexibly provide subscribers with higher data rates, ranging from 2.5 to 10 Gbit/s [40, 48-52], or increase the number of ONU connections [43]. For example, network providers can use either 25 GHz or 50 GHz spaced DWDM channels, to access 100 or 50 subscribers respectively. Because DWDM components and in particular optical sources can be easily affected by temperature, resulting in drifting of operating wavelength [44, 48], it has been currently established considerably costly to implement, precisely operate and maintain highly dense WDM-PONs [44]. In order to overcome this drawback, CWDM lasers and network elements in general have been introduced to provide less in count but cheaper to operate and interference free wavelengths for WDM-PON operation measuring up to 18

available channels between 1270 nm and 1610 nm with 20nm channel spacing [44].

Alternatively to demonstrate simultaneous transmission of increased number of subscribers and higher bandwidth provision achieved with current TDM standards for each, hybrid TDM and WDM PON architectures have been proposed [33, 50, 53-60]. Hybrid PONs are expected to comfortably supply each ONU with 73 Mbit/s or even 100 Mb/s connections in the near future, to conform with the FSAN recommendation for real-time triple-play servicing, while effectively managing capital and operation cost of network resources [33, 54, 58, 60].

As presented in Figure 1-4, a typical TDM-WDM hybrid PON architecture would utilise a single array waveguide grating (AWG) in the RN to achieve wavelength multiplexing for routing and time multiplexing for sharing of the optical source. To accomplish two-dimensional multiplexing and also simplify the ONU architecture, new developments have been adopted to avoid the requirement for dedicated optical sources in each ONU [32, 61-67]. By employing reflective semiconductor optical amplifiers (RSOAs) in each ONU to receive downstream data and modulate upstream data with continuous waves (CWs) originating at the OLT, the necessity of a wavelength-specific, local optical source is avoided [61, 62, 68-74]. At the first stage of deployment, a single TL and receiver in the OLT will be sufficient to centrally manage upstream and downstream transmission and dynamically distribute bandwidth among ONUs according to capacity requirement and service provisioning [18]. In case the network bandwidth demand exceeds the capacity of one TL, the presented architecture could meet the demand by providing an extra TL in the OLT to double wavelength provision at high traffic load ONUs while keeping the OLT inventory count low since the ratio of subscriber number to OLT transceivers is comparatively high.

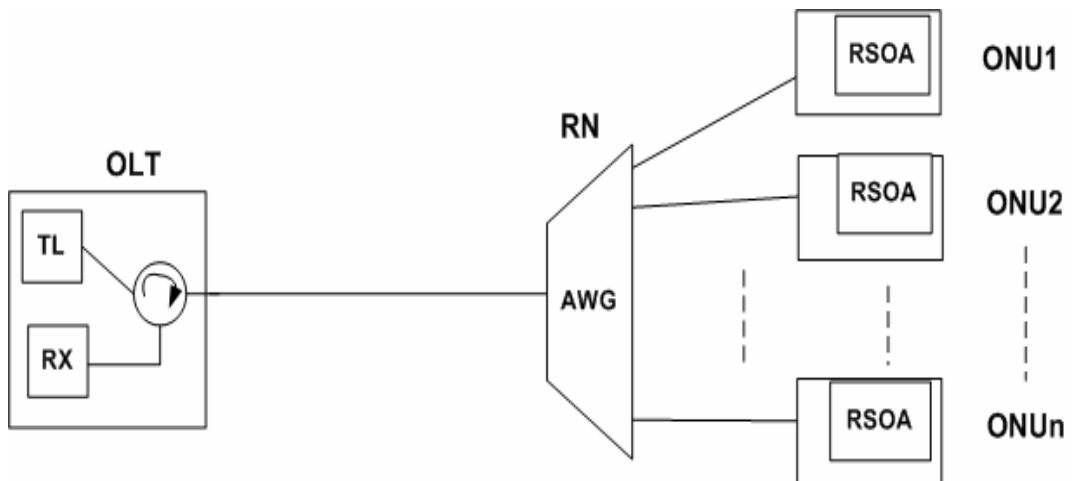


Figure 1-4 Hybrid TDM/WDM PON architecture

1.3 Contribution to Knowledge

Depending on the application requirements, network coverage and distribution of ONUs, PONs can be implemented in a fibre to the building (FTTB), FTTH or FTTC architecture [10]. Commonly in all three architectures, a passive RN in the form of a splitter/combiner is employed to distribute the downstream data from the OLT to ONUs and to combine the upstream data from individual ONUs to a single OLT. In downstream data is sequentially transmitted from the OLT before split equally in the RN to access all network ONUs. In the upstream direction, however, because of the random, burst nature of each ONU transmission, data collisions may occur alongside the shared medium between the RN and the OLT [22, 75]. In order to prevent data collisions and to fully utilise the network potential in the sense of centralised communication control in the OLT, medium access control (MAC) protocols, providing channel access control mechanisms, are adopted by GPON standards to manage data transmissions. Nevertheless, the GPON standards only designate the utilised MAC method and leave the detail algorithm open for researchers to further explore [30, 31]. Hence, the core research presented in this thesis focuses primarily on the data link layer of GPONs with the aim to explore and develop suitable dynamic bandwidth allocation (DBA) MAC protocols to demonstrate triple-play transmission by effectively managing

diverse services on demand and dynamically allocating channel capacity among network ONUs.

A novel dynamic minimum bandwidth (DMB) protocol has been developed to that extend to introduce multiple service levels into a FTTH-based GPON. Contrasting the proposed scheme with reported EPON and adapted GPON algorithms, simulation results have demonstrated reduced mean packet delay accomplishing up to a tenfold decrease at high network load. In addition, the demonstrated network performance in packet delay of high service level subscribers is sustained for increased traffic demonstrating network integrity and quality of service (QoS) according to subscriber service level agreement (SLA).

In a TDM-DBA protocol, upstream transmission time-slots for each ONU are assigned by means of grant messages, based on the report messages sent by each ONU to notify the OLT about their buffer queuing status. For the purpose of further optimising the QoS and SLA performance in GPON networks, the upstream transmission order of ONUs in each transmission cycle has been dynamically modified in the advanced-DMB (ADMB) protocol to improve the upstream channel utilisation rate by overlapping the last ONU upstream transmission period with fractions of the upstream idle intervals between bandwidth request, assignment and launch of packet transfer of the next polling cycle. Furthermore, to further increase the network performance, the real-time modifications in ONUs' upstream buffers during their bandwidth request-assigning process period are accounted to reduce packet waiting time in each ONU. Contrasting the ADMB and DMB algorithms, performance evaluation results for the former have shown a notable bandwidth efficiency reaching almost ninety-five percent of network capacity with a significant reduction in mean packet delay and packet loss rate to allow effective provisioning of high-bandwidth, time-sensitive multi-media services, such as HDTV and VoD particularly for high service level subscribers.

By reason of the exponential increase in PON deployment recently [76] and their envisaged application to terminate widely scattered subscribers effectively to common RNs and subsequently to considerably reduced number COs [77, 78], longer-span PON architectures extending their reach beyond 100 km and split size to 1024 have been attracting substantial attention [76-80]. To that extend the proposed integrated access/metro networks, could enhance QoS for various multimedia services, such as HDTV and VoD, since service providers and ISPs could directly apply centralised management of ONU requirements. However, when a protocol devised for standard access GPONs is introduced directly into 100 km typical long-reach architecture, the overall network throughput performance will be considerably reduced since additional transmission time-slots in each polling cycle will remain idle. This is due to an up to 500 μ s increase in packet propagation time from 125 μ s in 25km-PONs. To overcome this problem, a two-state DMB (TSD) protocol has been proposed to overlap the idle time-slots in each packet transmission cycle with a virtual transmission period to significantly increase channel utilisation rates as well as to reduce the packet delay and packet loss rate. Simulation results have presented a significant forty-five percent improvement in terms of channel utilisation rate compared to the DMB algorithm and further decrease in packet delay and loss rate, allowing for high network utilisation rates over extended periods of high-volume network traffic.

In GPON and long-reach PON architectures, the network capacity for each transmission direction is constant and can not be shared between upstream and downstream. To increase transmission efficiency by dynamically sharing the network capacity between downstream and upstream transmissions on demand, a WDM bandwidth allocation protocol has been developed to jointly manage the downstream and upstream data transfers. This has been achieved in the developed multi-wavelength DMB (MDMB) protocol by configuring the OLT frame to display time-slots occupied by either downstream data or un-modulated continuous waves (CWs). Unlike the developed algorithms for TDM-PONs, instead of accounting for the upstream and downstream capacity requirements

separately, they are integrated in a single parameter and time-slots assigned to ONUs according to their service levels and bandwidth demand for both transmission directions. The assigned bandwidth is then redistributed between the downstream and upstream transmission for each ONU to account for real-time requirements. It is anticipated that this research objective will assist in the further development of dynamic bandwidth and wavelength allocation MAC protocols for multi-wavelength operation of GPON standards [81].

1.4 Thesis Outline

Following this introduction, chapter 2 provides a detailed review of MAC layer advances in algorithm development to date. The industrial standard simulation platform OPNET Modeller [82] is introduced in chapter 3 to design a platform for DBA algorithm scheduling, and accordingly implement and evaluate the devised protocols at realistic TDM and WDM PON network traffic conditions.

The DMB algorithm and protocol evaluation in demonstrating dynamicity with respect to maximum network capacity and ONU service level and buffer queuing status are described in chapter 4 by modelling at this stage a standard procedure in exchanging grant and report packets to establish communication between the OLT and ONUs. With the intention of promoting enhanced channel utilisation, the association between ONU upstream transmission order and frame idle periods is further examined in chapter 5 to establish an advanced algorithm reducing ONU packet queuing time at upstream buffers in each data communication cycle.

The OPNET network simulation models defined for standard PONs have been redesigned in chapter 6 to account for the extension of network reach to 100 km and investigate the channel throughput and packet loss rate performance due to the inevitable increased propagation delay of grant and report messages in long-reach PONs. In particular the rescheduled protocol capability in supporting

real time services by means of sustained packet delays for various ONU service level agreements has been extensively examined.

Chapter 7 concentrates on the application of an alternative simulation model and protocol to dynamically arrange bandwidth between upstream and downstream transmissions for each ONU in WDM-PONs. Significantly the signal round trip time (RTT) feature of the employed TL, associated with its wavelength turning time and the OLT/ONU signal processing times are exclusively analysed to demonstrate multi-wavelength operation.

Finally, chapter 8 presents a summary of the aspirations, contribution and developments of the research presented in this thesis followed by immediate and far future research drives with particular emphasis on frame formatting for multiple wavelength operation of standard, splitter-based GPONs.

Chapter 2

Passive Optical Networks: Architectures and Protocols

This chapter provides a review of existing DBA protocols related to relevant PON structures. Following a short introduction, the bandwidth allocation mechanisms of TDM-PON protocols are investigated by means of the assignment of grant and report packets to fully utilise upstream capacity and guarantee QoS. Future access network structures are described in subsequent sections with particular emphasis on P2P WDM and P2MP hybrid WDM/TDM topologies leading to long-reach PONs to establish the network architecture and algorithm philosophy modifications necessary to develop effective transmission protocols.

2.1 Introduction

Passive optical network infrastructures, such as the standardised EPON and GPON and increasingly investigated longer-reach PON, are implemented in a tree topology, to maximise network coverage with minimum possible splits to reduce optical power loss, in which an OLT provides access to multiple ONUs [31, 83-86] through a common optical path spanning from the OLT to the RN. Due to deeper fibre penetration and generally passive components in the field, TDM-PONs are economical for providing broadband access services [84, 87]. To prevent upstream data collisions in the shared pathway, MAC protocols have been defined to manage ONU traffic statically or dynamically demonstrating accordingly static or dynamic bandwidth allocation [28]. In a static bandwidth allocation algorithm,

each ONU is assigned with a constant bandwidth regardless to its actual bandwidth demand. As a result, the allocated bandwidth might either not be fully utilised, in the case of ONUs with light traffic requirement or not be adequate to accommodate heavy traffic load ONUs, resulting in both scenarios to inefficient bandwidth utilisation rate. In contrast a dynamic MAC protocol could more successfully allocate bandwidth according to ONUs' instantaneous buffer queue status increasing the bandwidth utilisation rate [88-91]. Research initiatives in MAC protocol development over the years have attempted to enhance further bandwidth allocation of standardised PON topologies, tracing back to APONs [92, 93] and more intensively to more recent and lately deployed EPONs [89, 94-96]. In common to all these topologies, the feeder pathway is shared in the time domain, and as a result each ONU can utilise the whole upstream optical carrier capacity for defined, according to network penetration, and in most cases flexible duration time-slots, assigned by the OLT [97].

To extend the scope of the work presented in this thesis to typical, yet not standardised WDM-PONs [32, 68-70] a multi-wavelength protocol will be investigated in following chapters. In contrast to TDM topologies, network capacity is shared in the spectrum domain [15, 33, 98] by assigning each ONU to a unique wavelength for data communication, forming logical point-to-point links between the OLT and ONUs. Since ONUs could access the network simultaneously the overall transmission bandwidth for each ONU in a WDM network is considerably increased at the requirement of dedicated transceivers. Nevertheless, the dedicated devices also increase significantly the cost of WDM network deployment [3, 76]. This drawback could be resolved by employing increasingly researched, although restricted currently to physical layer, reflective architectures to demonstrate hybrid TDM/WDM PONs [67, 76] where bandwidth is assigned as proposed in subsequent chapters in combination between time and wavelength.

Driven by incumbent initiatives to deploy WDM-PONs and the very recent publication of the multiwavelength GPON standard, ITU-T 984.5 [81], future

initiatives in MAC protocols for GPONs would be expected to concentrate on multi-wavelength operation over standardised GPON architectures.

2.2 TDM Bandwidth Allocation Protocols over PONs

In GPON and EPON standards, a TDM-MAC protocol is employed to manage network bandwidth among ONUs [60, 75, 99, 100]. As presented in Figure 2-1 data transmission in downstream is broadcasted sequentially from the OLT, through the feeder section, to the splitter/combiner and subsequently split to multiple copies to reach all ONUs. On reception, individual ONUs detect only packets destined for them ignoring all others [75]. In contrast, each ONU upstream is assigned with a dedicated time-slot to transmit data, by means of the applied MAC protocol, avoiding data collisions alongside the shared feeder section [101].

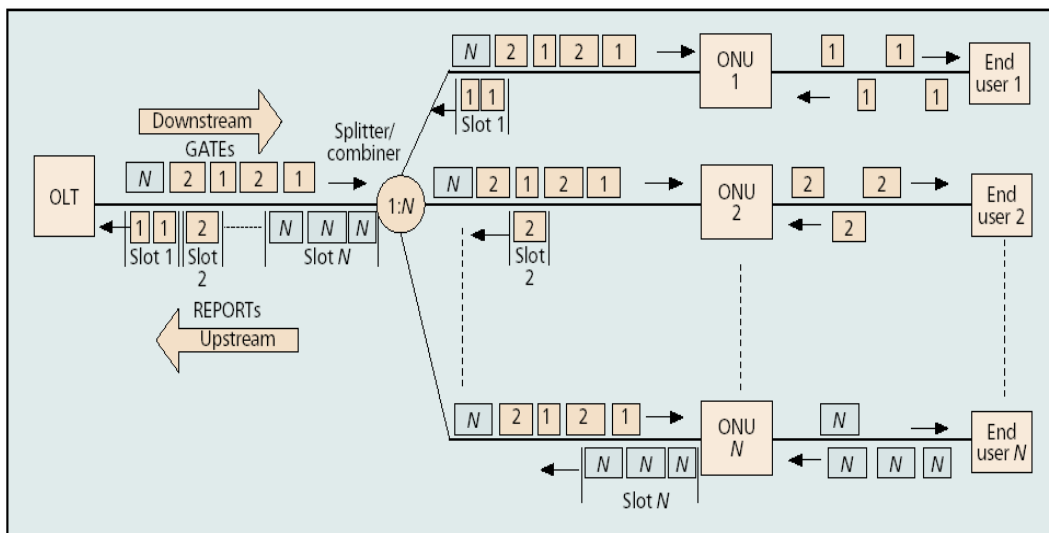


Figure 2-1 The system architecture of a PON [75]

The fundamental functionality of a TDM-MAC protocol is to allocate constant time-slot lengths for each ONU at regular periods regardless of its bandwidth requirement. As shown in Figure 2-2, a practical limitation of constant TDM protocols is the demonstrated inefficiency in time-slot assignment since independently of whether ONUs are silent, or exhibit low traffic load by means of

moderate buffer queuing performance, the same, constant time-slots are assigned at each cycle of operation indicating that fractions of the allocated time-slots remain idle and equally important incapable of being transferred to high bandwidth required ONUs. In the latter, random packets will have to be buffered for various polling cycles since their capacity requirement exceeds the relative assigned bandwidth. To overcome these drawbacks TDM-dynamic bandwidth allocation (TDM-DBA) protocols have been developed to increase the transmission efficiency and to reduce the packet delay by dynamically allocating upstream time-slots according to ONUs' bandwidth demands and overall network capacity [86, 102-104].

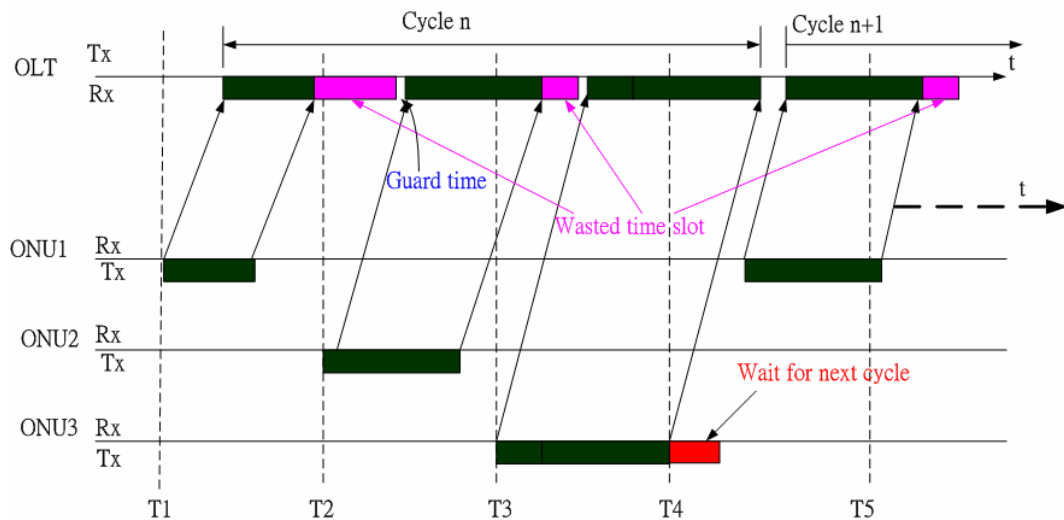


Figure 2-2 Constant time-slot TDM MAC polling diagram

In order to precisely arrange the upstream time-slots among ONUs, a grant message is employed by the OLT to inform ONUs about dispensed upstream time-slots which are assigned based on the report messages sent by ONUs to notify OLT about their buffer queuing status [84, 85, 95, 105-112]. Nevertheless, the propagation delay of grant and report messages, could impose additional waste in transmission bandwidth of higher altitude to constant MAC protocols [104]. As presented in Figure 2-3, considerable bandwidth is misused in each polling cycle since significant upstream time-slots are not utilised to maximum capacity. With the purpose of increasing upstream channel utilisation rate, an OLT-based polling

scheme, called interleaved polling with adaptive cycle time (IPACT), has been proposed for EPONs to display time-overlapping between the grant and report messages propagation among OLT and ONUs [85].

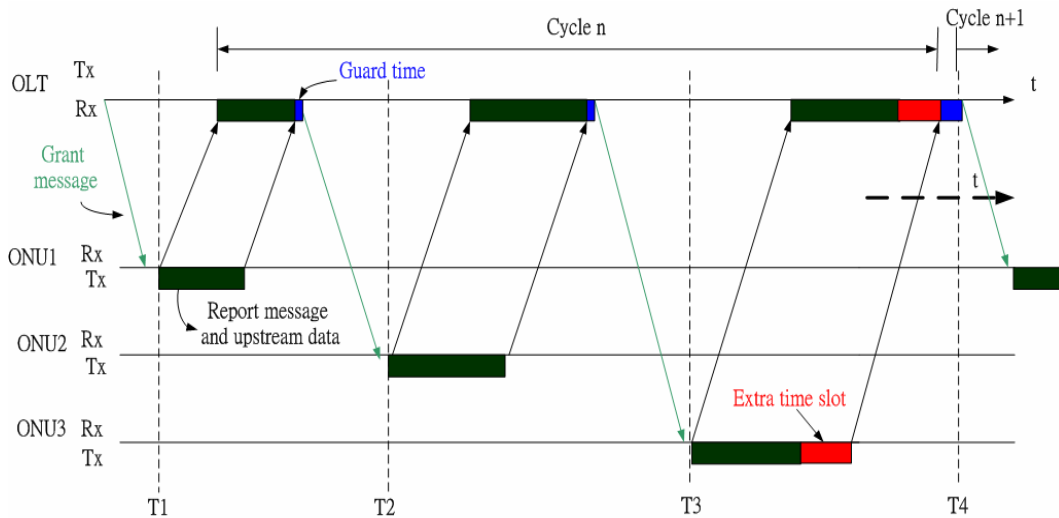


Figure 2-3 Dynamic TDM MAC polling diagram without overlapping grant and report messages propagation

In IPACT, report messages representing each ONU contain information of not only their buffer queuing status but also their RTT. Based on this information, on receipt of the report message from ONU₁ for example, the OLT could estimate its upstream transmission period and the propagation delay of the grant message for ONU₂. Therefore, the grant message could be transmitted and reach ONU₂ before ONU₁ has completed its upstream transmission, preventing the accumulation of grant and report messages intercommunication time. As shown in Figure 2-4 (d), the starting bits of ONU₂ user data in a given cycle arrive at the OLT soon after ONU₁ has completed its upstream data transmission with a small guard time interval in between.

In addition, to avoid an ONU with heavy loading monopolising the entire available bandwidth, IPACT limits the maximum transmission window for each ONU. As a result, the OLT in each cycle could assign bandwidth on request for data transmission as long as individual ONU requests do not overpass a maximum.

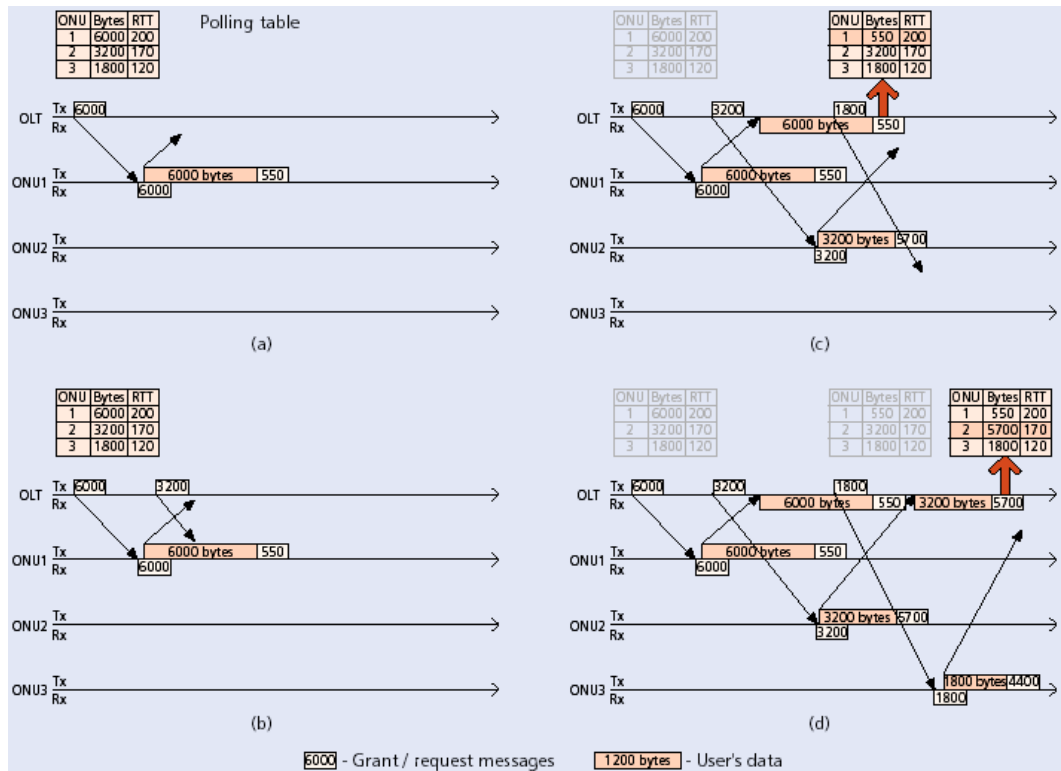


Figure 2-4 Steps of IPACT polling diagram

A straightforward limitation of IPACT results from the fact that an unnecessary packet delay is introduced into the network in an increasingly common case that the total bandwidth requirement from all ONUs in one cycle is less than the overall network capacity but the bandwidth request of distinctive ONUs exceeds the maximum transmission limit. According to IPACT, the additional demand will be buffered hopefully until the next polling cycle. Furthermore, the signal processing time in the OLT and ONUs as well as the guard time between two adjacent upstream windows are fixed. Even if the polling cycle of low traffic ONUs is reduced by assigning shorter time-slots, the proportion of guard time and signal process time in a cycle is relatively higher. As a result, the network performance in terms of upstream channel utilisation rate becomes worse. To overcome the drawbacks causing low channel utilisation rate and long packet delay, the concept of a guaranteed bandwidth by means of providing a fixed guard time has been proposed to define a minimum transmission limit, instead of a maximum in IPACT, for each ONU to satisfy their basic service requirements

[102, 106, 110, 111, 113]. With this mechanism in place, the OLT would have to first receive all report messages from ONUs before it initiates the bandwidth allocation process which is practically expected to result in wasted time-slots during two successive polling cycles. This is shown in Figure 2-5, demonstrating clearly that if certain ONUs are not operating at full load, like for example ONU₁, the OLT would dynamically assign unused times-lots to those ONUs whose requirement in bandwidth surpasses the initially assigned “guaranteed minimum bandwidth”. Nevertheless, ONU service level agreement or differentiation are not considered in defining the surpass ONU bandwidth and as a result not allowing for network priority.

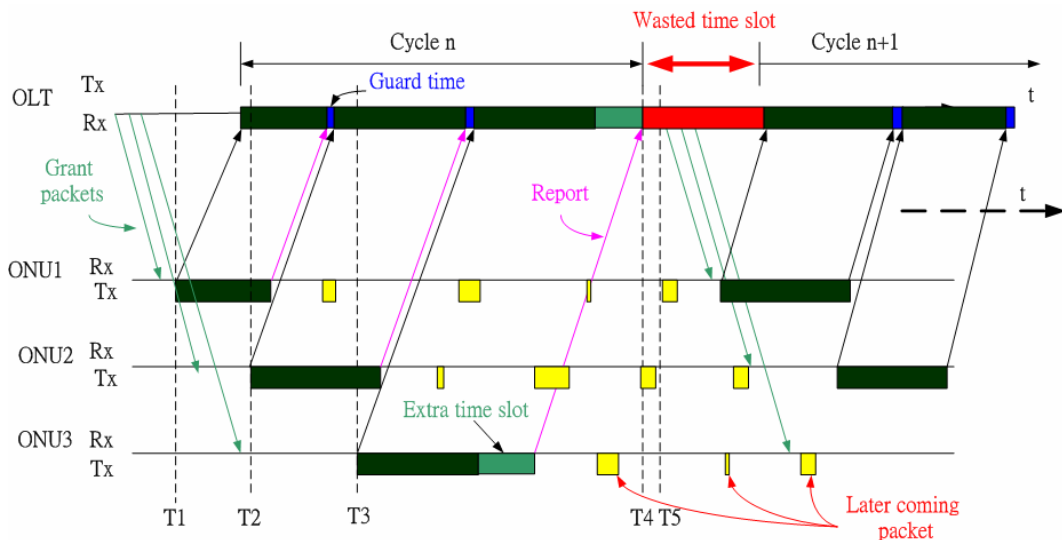


Figure 2-5 Steps of polling diagram in guaranteed minimum bandwidth allocation protocols

2.2.1 Quality of Service over TDM-DBA Protocol

In view of service centric access networks where service differentiation from the point of view of accommodating various service priorities in accessing a network [31, 114] and service transparency by means of one protocol to fit all [115], multi-media aware DBA protocols should demonstrate except from increased channel utilisation rates, effective packet delay according to service requirements and service level agreement between ONUs when accessing the network. Individual real time services, such as IP telephone, internet radio, remote

surveillance, video-on-demand, video conference for example, require low packet delay and low packet loss rate, while FTP or e-mail access could tolerate longer delays.

With the intention of guarantying acceptable packet delay to fulfil QoS requirements, the priority of communicating various classes of service needs to be considered in developing TDM-DBA protocols. For example, depending on time sensitivity, network traffic in EPONs is mapped into three classes, namely expedited forwarding (EF), assured forwarding (AF) and best effort (BE), representing high to low priority in accessing a network [75, 84, 86, 110, 113]. Corresponding DBA protocols, such as the SLA-aware dynamic bandwidth allocation algorithm (SLA-DBA) [113] and the DBA with priority transmission order (DBA-P) [111], distribute the upstream available bandwidth per class of traffic rather than per ONU. As shown in Figure 2-6 before the OLT assigns transmission time-slots in a given polling cycle, every bandwidth demand is divided into one of the classes mentioned above and each class of traffic is then allocated with a guaranteed bandwidth that was agreed between the network provider and customers. The unused bandwidth is then proportionally assigned to all classes according to their demand.

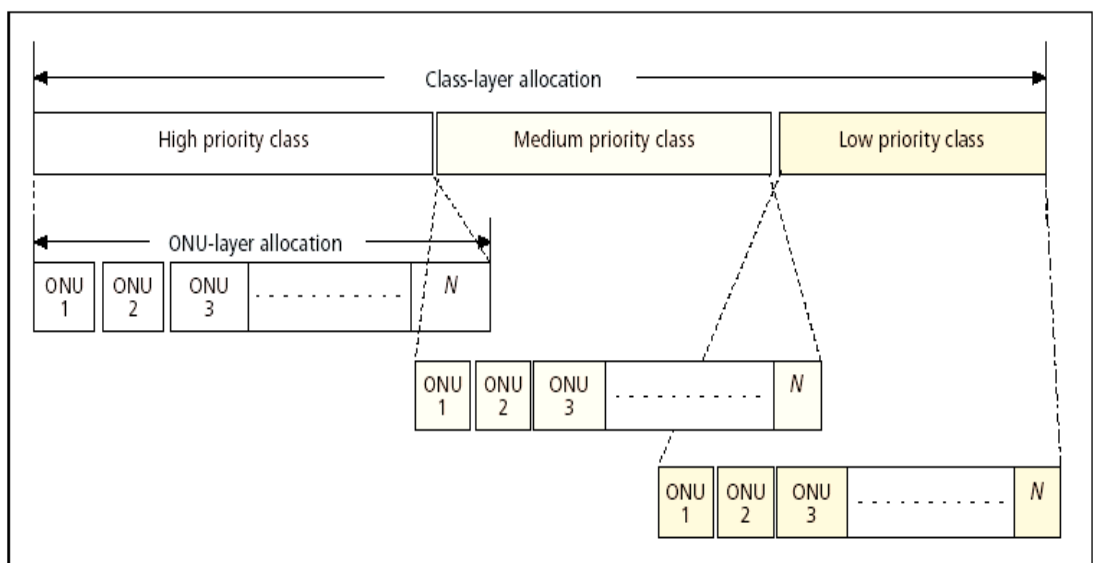


Figure 2-6 The principle of class-based bandwidth allocation [84]

While the SLA-DBA and DBA-P protocols provide a guaranteed bandwidth for each class of traffic, some other TDM-DBA protocols, such as the dynamic bandwidth allocation with multiple services (DBAM) [84], two-layer bandwidth allocation (TLBA) [75], start-time fair queuing (SFQ) [106] and the modified SFQ (M-SFQ) [110] protocols, assign every class of traffic a weight between 0 to 1 to represent the priority of accessing the network and then flexibly calculate a maximum window for each class by multiplexing the available bandwidth with the corresponding weight. By considering difference classes of service, these TDM-DBA protocols are able to provide clients with low packet delay, low packet loss rate real-time services in various communication conditions [84, 111].

Common in all protocols presented above only a single aggregate data rate and one SLA are accommodated for ONU access [3, 83, 113, 116, 117]. This is because they perform logical allocation of resources on the basis of either FTTB or FTTC network architectures where multiple subscribers are connected to a single ONU [14, 113]. Consequently ONU upstream packets comprise information from multiple clients not allowing for the provision of SLA to individual client's access.

Nevertheless, as suggested in FSAN, the required bandwidth for each ONU is around 73 Mbit/s [14, 15] limiting the maximum number of subscribers in a GPON network to around 32 for 2.4 Gbit/s aggregate rates. As a result, the FTTH architecture is more likely to be the next generation optical access network structure to provide triple-play services [13, 14, 21, 42, 118-121]. In addition, as defined in the GPON standard [27], multiple aggregate data rates are defined to transmit data. Thus, this research has concentrated in developing FTTH-based TDM-DBA protocols with an ability to automatically adapt and achieve QoS by means of SLA at different operating aggregate data rates and therefore being universally applicable independently of distinctive GPON deployment characteristics. To achieve this objective, a guaranteed minimum bandwidth will be provided to each ONU as mentioned before dynamically and according to the network capacity and ONU SLA instead of being set to a constant value. This

property allows for scalability in the logical domain and protocol transparency in the case the network capacity or the number of ONUs changes since the OLT can still distribute upstream bandwidth without requiring modifications in the MAC protocol.

2.2.2 Differentiated Services over GPON

In contrast to EPONs, GPON standards instead of mapping network traffic into EF, AF or BE classes, define five class-of-service (CoS) types [28, 115, 122, 123] each delivered by a transmission container (T-CONT) to enable QoS implementation in upstream direction. As presented in ITU-T Recommendation G. 983.4 [88], a priority mechanism is related to T-CONTs in terms of fixed bandwidth, assured bandwidth, non-assured bandwidth, best effort bandwidth representing high to low priority of accessing the network respectively. The fifth CoS results by the combination of two or more of the other four stated classes. The associated mechanism of each T-CONT is presented and described below [28, 31, 114]:

- T-CONT 1: It is intended for the emulation of leased line services and is supported by constant bit rate with fixed periodic grants to offer strict demands for throughput and delay. This class is the only static traffic not serviced by DBA algorithms [31, 114, 124].
- T-CONT 2: This container is intended for a variable bit rate requiring low delay and low packet loss rate transmission. The assigned bandwidth for this kind of services, such as HDTV and VoD, is ensured in the SLA and assigned based on the bandwidth requirement in each polling cycle.
- T-CONT 3: It is based on a reservation method to provide medium delay, and low packet loss rate connection. It is supported to provide better performance than T-CONT 4 service and is offered at a guaranteed

minimum data rate. Any additional bandwidth requirement is counted in each polling cycle and assigned when available.

- T-CONT 4: This container is intended for best effort services providing a high delay, and high packet loss rate transmission. This class of services, such as browsing and FTP, is serviced after the previous service classes are satisfied.
- T-CONT 5: The last container is not really a different class but a combination of two or more of the other four classes and is reserved for the system designer to choose and operate.

The concept of T-CONTs provides a guideline to communicate various service classes from clients. An efficient MAC protocol is, therefore, required to incorporate the T-CONT mechanisms in appropriate algorithms which would in turn allow for various services to be accommodated in a GPON.

2.3 Multi-wavelength Dynamic Bandwidth Allocation Protocols

Following the inevitable adaptation of emerging broadband applications, such as VoD and HDTV, available access network bandwidth would have to be significantly increased [15, 19, 44]. When the demand in bandwidth eventually exceeds the limited capacity of TDM topologies, network capacity per user could be directly enhanced by either increasing the number of operating wavelengths or by decreasing the number of subscribers in a network [33-35]. Significantly WDM architectures have already been considered to provide 1 to 10 Gbit/s transmission rates per subscriber. Nevertheless, the components cost of deploying such multi-wavelength networks has limited their applications in the last mile connection [19, 44]. In addition, for the near future the ultimate access bandwidth per client is not expected to exceed 73 Mbit/s [14, 15]. Currently deployed

TDM-GPON standards are considered adequate in supplying demand alleviating, for the time being, the need of WDM-PONs.

On the contrary providing a smooth transition from TDM-PON to WDM-PON and demonstrating interoperability over a single platform has already become a popular research topic [18, 19, 53] while hybrid TDM/WDM PON architectures have grown to be one of the leading technological propositions in the optical access domain. For example, Figure 2-7 presents such an architecture developed at Stanford University [33, 53-55] employing tunable lasers (TLs), AWG and thin-film WDM filters, represented by Ch 1-16 in Figure 2-7, to demonstrate a hybrid 4 logical PONs network.

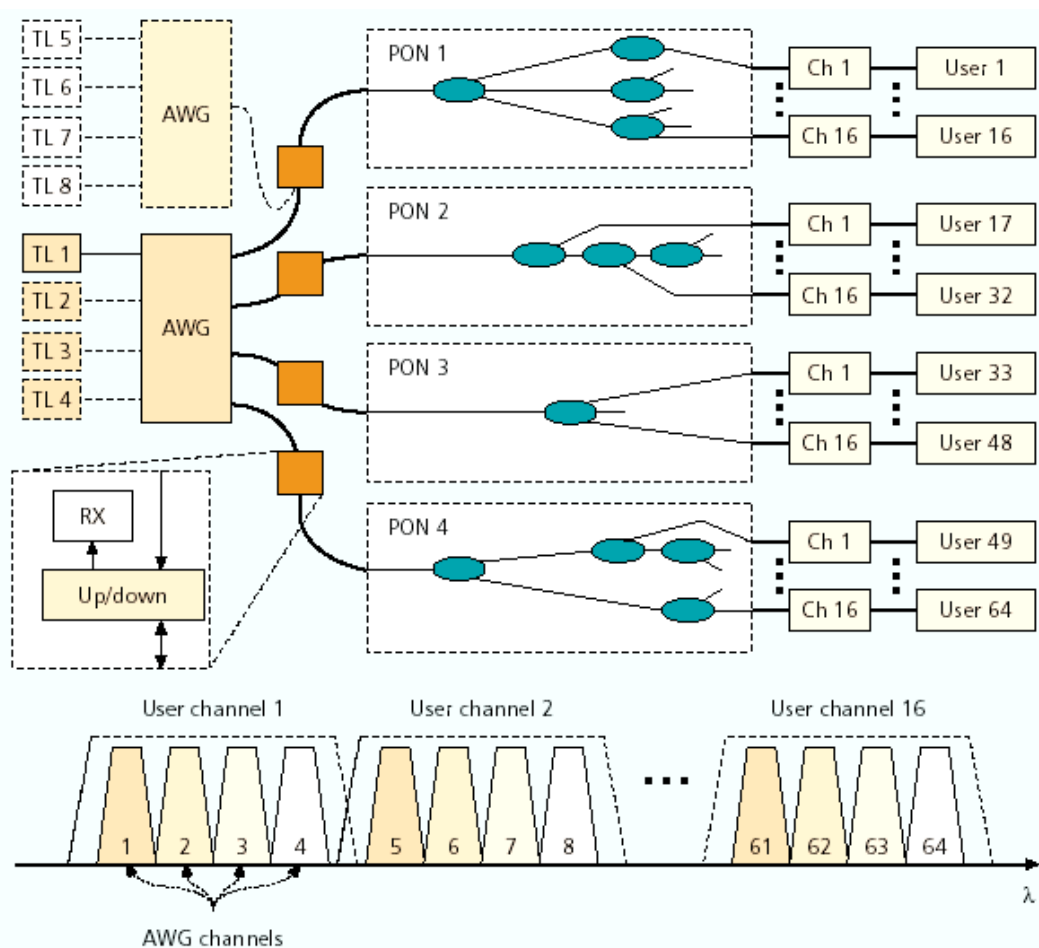


Figure 2-7 The SUCCESS-DWA PON architecture and the corresponding wavelength bands for AWG channels and thin-film WDM filter [33]

By tuning the various TLs' output wavelength, each TL can address any ONU across all of physical PONs at any given time to flexibly adjust the downstream capacity. At the early stage of deploying the network, instead of sharing time-slots to access communication path in TDM-PONs, each ONU can share the downstream time-slots to utilise only one TL, so the deployed cost of TL can be shared among PONs. Once the downstream bandwidth demand in the network exceeds the capability of TL₁, one or more TLs can be employed in the OLT to boost up the downstream network capacity providing powerful scalability in terms of downstream network capacity. Nevertheless, in upstream each ONU using the same optical carrier in a PON still needs to share the fixed capacity in time.

In order to increase the upstream network capacity by sharing upstream channel in frequency domain and to simplify the ONU device by taking off light source at the ONU, RSOAs to concurrently detect downstream data and modulate upstream CWs, generated in the OLT and transmitted downstream in parallel with data, have been commonly employed in WDM architectures to display colourless, reflective ONUs, also expected to expand to TDM ONUs to sustain hybrid access network operation [47, 62].

Initially the application of colourless ONUs was proposed in combination with the use of two fibres to connect the OLT with each ONU [61, 62]. One is employed for the transmission of downstream data and un-modulated CWs, and the other is to carry the modulated CWs upstream. In addition since two respective wavelengths are required to transmit upstream and downstream data for each ONU, restricting as a result network penetration, a more economical hybrid architecture, shown in Figure 1-4, has been widely adopted based on a single fibre reel, where each ONU's upstream and downstream data is communicated using a single wavelength [50, 62, 69, 70, 125].

This can be achieved in the data link layer by accounting for time-slots in downstream frames, as shown in Figure 2-8, solely to transmit the un-modulated CWs [68, 70, 71, 126]. Also by controlling the allocated time-slot lengths between

upstream and downstream, the OLT could centrally manage and adjust each direction's capacities suggesting that instead of sharing the upstream channel in the time domain as in typical TDM-PONs, ONUs in the hybrid time-share the TL to allow bidirectional bandwidth allocation on demand [68, 69]. Although the current architectures have recorded the physical layer performance of reflective WDM/TDM-PON, the mutual application of wavelength and bandwidth allocation in a new protocol is expected to enhance the hybrid performance in all performance evaluation measures. This can be achieved, as will be described in detail in successive chapters by dynamically distributing downstream and upstream capacity along with ONUs' SLA and instant buffer queuing status.

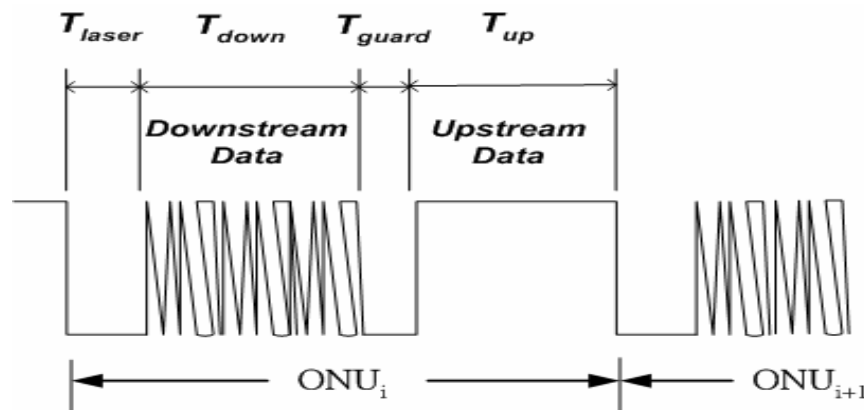


Figure 2-8 Reflective WDM-PON frame structure [68]

2.4 Bandwidth Arrangement in Long-reach PON

Aiming to reduce deployment cost equally as much as operational cost in future optical access, a longer-reach, increased split, reaching up to 1024 subscribers, network has been investigated to terminate end users directly to the core edge nodes [67, 127-129]. Since the service coverage range of a CO in access ideally equals the square of the connection length, by increasing the maximum connection distance of current PONs from a typical 20 km to around 100 km proposed for long reach applications, the coverage range of a CO could be increased by a factor of 25. In practical terms that would suggest dramatic decrease in the number of COs required to meet demand. In that sense the access network assimilates characteristics of the core network by means of sharing the

cost of basic network elements among a larger number of ONUs, reducing significantly installation, maintenance and operation cost [67, 79, 128, 130].

To implement a full service access network successfully, multi-media services, such as voice on demand and video-conference, should be provided by means of an appropriate MAC protocol to clients on demand. Due to the multiple nodes a signal needs to go through, if the metropolitan network adopts a best effort approach to connect COs with a media centre, real time traffic provision can not be guaranteed with acceptable QoS [128, 131]. By using a 100 km-reach GPON, consolidating the metropolitan and access networks, traffic originating at the subscribers' premises would be directly transmitted to an edge switch at the core network to increase the QoS by reducing the transmission delay [79, 128, 131].

In such an infrastructure due to the increased splitter ratio as opposed to the standard 32 ratio considered in standard GPONs, would require considerable advancement in the already considered network structures and MAC protocols to reduce the effect of long propagation delay and to provide sufficient bandwidth for on-demand, triple-play access [76, 80]. Architecturally this has been approached from the point of view of applying again wavelength in combination with time multiplexing [3, 76, 132-135]. Figure 2-9 demonstrates such a hybrid architecture comprising of an AWG in the RN, denoted as local exchange, for multi-wavelength routing and erbium-doped fibre amplifier (EDFA) to boost the downstream and upstream optical signal [76].

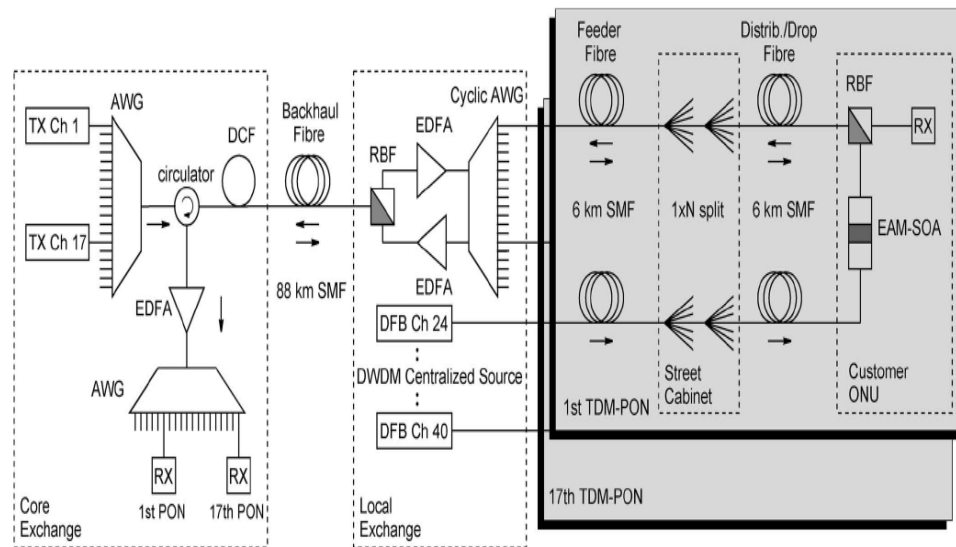


Figure 2-9 long-reach WDM-TDM PON architecture [76]

The network philosophy is based on the interoperability of multiple virtual TDM-PONs, each of which is allocated one or two specific wavelengths for both downstream and upstream transmission. In downstream, data addressed to individual virtual PONs is modulated and transmitted on different dedicated optical carriers and as a result downstream data for each virtual PON could be transmitted simultaneously and independently. Similar operation is adapted in the upstream. Since the 1024 ONUs are distributed over multiple virtual PONs, each virtual network can display sufficient bandwidth by a single wavelength to provide its users multi-media services successfully. However, in contrast to standard 20km-reach TDM-PONs, the propagation delay in the 100km-reach network is significantly increased from 100 μ s to 500 μ s implying limitation in real time provision if not administrated appropriately by means of a MAC protocol.

The application of typical TDM-DBA protocols as presented in previous sections in this chapter, would result in a 1000 μ s idle periods associated with the grant and report messages propagation time in each polling cycle, greatly reducing the upstream channel utilisation rate as presented in Figure 2-10. To utilise every possible available upstream time-slot with minimum possible buffering taking

place in ONUs a dedicated long reach DBA protocol should be developed to support multimedia services with QoS by improving the channel utilisation rate and reducing the effect of long propagation delay.

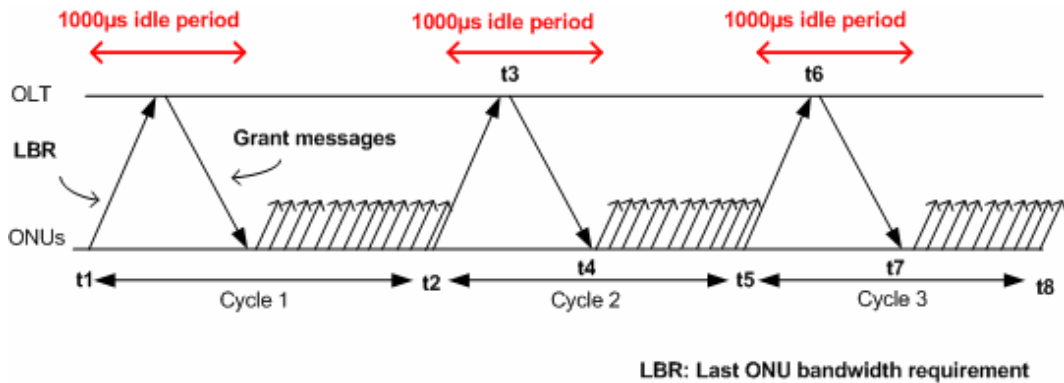


Figure 2-10 Steps of DBA polling diagram in 100km-reach PON

2.5 Summary

Data formatting and transfer mechanisms in access networks, alongside the abiding development of scheduling, routing and switching methodologies in the core network have been increasingly researched recently with the aim of demonstrating transparent protocols for end to end connectivity. To that effect, MAC protocols for EPON applications have been reported to allocate available bandwidth among ONUs in time displaying controlled dynamicity and sensible channel utilisation rates and packet delay.

The lack of TDM-DBA protocols for currently deployed GPONs, offering enhanced and flexible data rate connectivity and the possibility of a transparent protocol for ATM and IP networks, has defined the research ground of this research programme aimed to demonstrate for the first time DBA protocols for standard GPON architectures and successively adapt them to transfer data at longer distance, increased volume subscribers and hybrid infrastructures of the future employing wavelength grooming for increased capacity connections. Following an overview of the published TDM-DBA algorithms in EPONs, the

research specifications of the undertaken study were identified with the concept of providing QoS beyond a flexible but constant network capacity arrangement for fixed service level ONUs. Therefore, alongside the FSAN recommendations for bandwidth and extensively service provision for clients, FTTH DBA protocols have been developed aiming for real-time, on-demand distribution of network resources depending on service level agreement and as a result variable QoS priorities.

To implement the algorithms, standard and widely researched and adopted network architectures of TDM GPONs, long-reach GPONs and hybrid TDM/WDM PONs have been extensively described identifying protocol requirements and performance measures during communication set up by means of the propagation time among report and grant messages between the OLT and ONUs and the actual data transfer procedure by means of prioritising OLT access by ONUs based on their service arrangements and level agreement.

Chapter 3

Network Simulation Model on OPNET Modeler

Following the analysis of standard and extended PON architectures to demonstrate network scalability and upgrade, and having identified in particular the development specifications of associated protocols to exhibit dynamic resource allocation, chapter 3 is concerned with the programming and modelling aspects allowing for network implementation and algorithm evaluation. To that effect the industrial standard OPNET Modeler is utilised to distinctively device individual network elements, packet formats and traffic models. The performance and reliability of which have been assessed by simulating a well known DBA algorithm.

3.1 Introduction

Recent advances in photonic communication networks require modelling and simulation tools of ever increasing scope and complexity. With valid and credible models, simulations are used heavily to investigate and assess new solutions before implementing testbeds and field trials. In many cases, major performance improvements are obtained by combining analytic approaches with pure simulation techniques. This chapter reviews the application of the industrial standard simulation package OPNET Modeler [82] to model typical TDM-PON logical infrastructures and subsequently assess them quantitatively by means of performing MAC algorithm simulations in the presence of GPON formatted traffic.

As opposed to real system measurements, leading naturally to a higher degree of accuracy compared to analytical measurements and simulations, the major advantage of the later is that they can demonstrate the feasibility of a virtual but fully deployable network and define in detail individual network element operation characteristics with increased confidence prior to its actual implementation. This becomes of even higher importance in networks research where real system measurements would imply either deployment of a full scale network in the form of a testbed or the disruption and reconfiguration of a commercial network which is considerably inefficient or even impossible to achieve.

Besides there are further criteria, which might argue in favour of the significance of simulations such as the cost to set up a testbed over which the developed algorithms will have to be eventually programmed to dictate network operation, the re-configurability and time conservation since parallel simulations could be performed and network architecture or protocol modifications directly implemented, the measurability in the presence of seldom occurring effects and the reproducibility of results in case random measurement errors occur allowing for replicating the exact measurement conditions making troubleshooting simpler.

To that extend, OPNET is built on top of a discrete event system and has been used as a communication network simulation platform throughout various research programmes [82]. It provides a detailed modelling tool to simulate network principles by modelling each event occurring in a system and processing the modelled network through users' definition. As present in Figure 3-1, OPNET employs a hierarchical domain structure comprising the project editor in the network domain to provide network connectivity, the node domain where the network node models are defined, and the process domain where individual node models are programmed by means of equivalent process models to conduct specific operations. To achieve network integration, system designers normally need to define the protocol packet formats in the individual node models, the

transition mechanism in each process model and the transceiver modules used in each node.

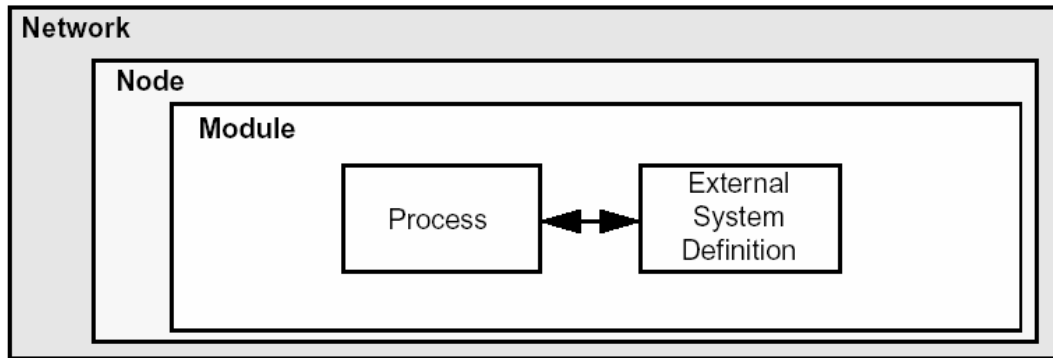


Figure 3-1 Relationship of hierarchical levels in OPNET models

At top level, complete networks are modelled in the network domain using the OPNET project editor offering a congregation of sub-networks, nodes and links. The functionalities of each node and link are specified in the OPNET node and link editors respectively. To integrate various operations in a node, each node model comprises several modules. Some of which are programmed in the process domain and edited in the OPNET process editor by using C programming or added directly from the OPNET library. Due to their domain architecture and programmable capacity, the network, node, and process modelling environments provide users with the flexibility to easily modify network operation principles by only reprogramming or redesigning the element of significance across layers [136].

With the aim of evaluating a standard GPON simulation model in the network domain incorporating a variety of processing models in the form of developed MAC algorithms, the IPACT protocol [85] presented in the previous chapter has been initially simulated over a duplicated EPON network model. This was considered necessary at this stage to provide a means of reference for the efficiency of the developed OLT and ONU node models, repeatedly employed throughout this research. Although the IPACT protocol is intended for EPON applications, the algorithm has been consequently applied directly to assess the

bandwidth allocation performance of a self-developed GPON architecture, being also of tree topology, by redesigning the frame format and readjusting the time to transmit the grant and report messages between the OLT and ONUs according to the GPON standard [28].

IPACT has been strategically considered appropriate to define performance measures of the devised GPON network model by means of channel utilisation rate since it has outperformed up to date EPON DBA algorithms, such as the dynamic credit distribution [86], guaranteed minimum bandwidth [111], two-layer bandwidth allocation [75] and intra-ONU bandwidth allocation schemes [83] already presented in the previous section and most importantly due to the complete absence of developed GPON MAC protocols at the commencement of this research programme.

3.2 The Project Editor

The project editor in OPNET provides the interface for network simulations, by implementing the test architecture in the form of available network element libraries or user-defined sub-models and performance evaluation. These operations are successfully compiled only in the presence of fully functional node and process editors to define individual blocks. An example of a project editor environment is shown in Figure 3-2 displaying the logical topology representation of a standard GPON/EPON tree architecture where independent bus lines are used to model the broadcasting downstream and time-sharing upstream data allocation processes. Also shown in Figure 3-2 are the individual nodes comprising, the OLT, ONUs and also the downstream/upstream links. Since the developed DBA protocols presented in this thesis are primarily focused on the management of upstream data transmissions, no downstream data is generated at this stage to simplify the network simulator. As a result only grant messages are produced in the OLT model necessary to notify ONUs about their upstream transmission windows.

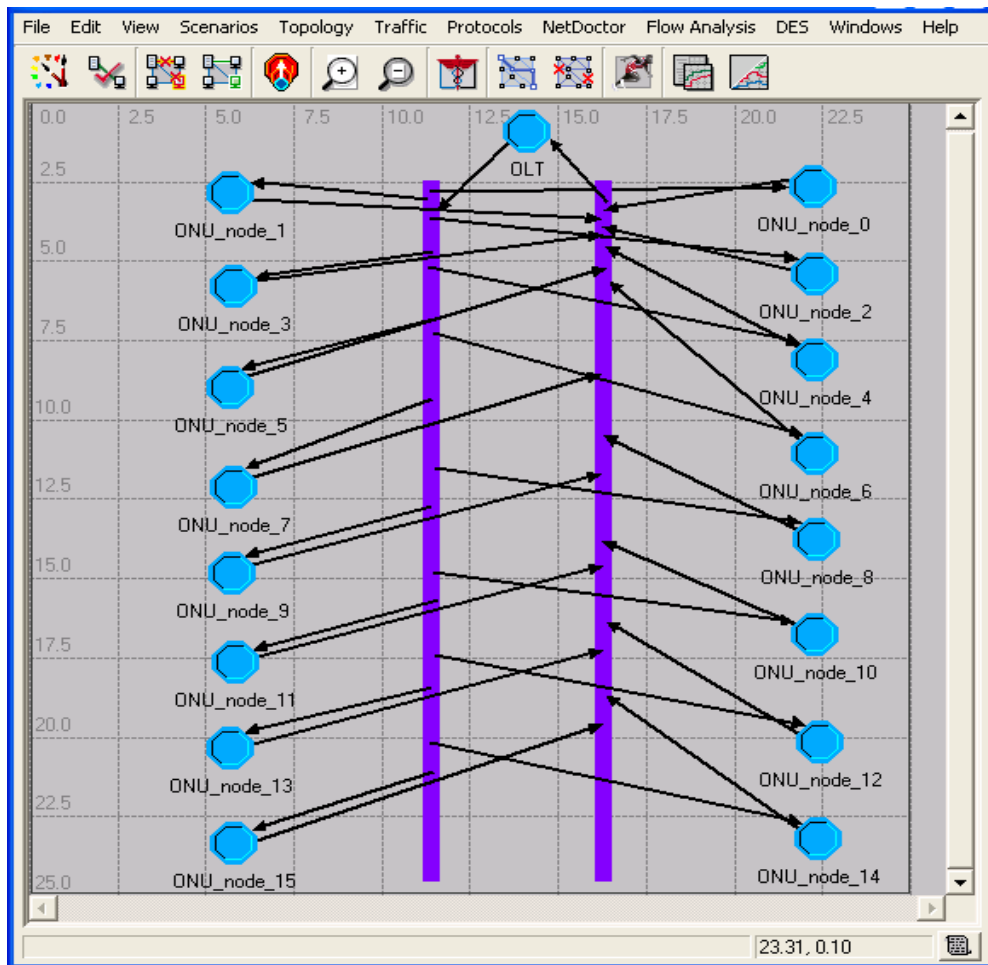


Figure 3-2 logical PON structure

In a nutshell, the functions of the basic network elements are summarised as below:

- OLT node model: The major functions of the node are to define the number of ONUs connected in the network, process the integrated MAC protocol for data exchange and finally gather the transfer statistics.
- ONU node model: Apart from gathering current processing environment (CPE) statistics, it is designed to record the buffer queuing status and transmit data at designated upstream time-slots. Depending on network application, each ONU node model, with the assistance of the OPNET

data generator module, could be programmed to sustain various traffic characteristics.

- Downstream/upstream links: These links are used to model the transmission characteristics of the feeder fibre. Specifications such as operating data rate and propagation delay can be defined through the “attribute interface” provided by the standard OPNET library.

Following configuration of the OLT and ONU node editors, the developed MAC algorithms are embedded accordingly to define the individual node processing models which define their and extensively the complete network’s functionality.

3.3 OLT Node Model

To simulate a MAC protocol, the design of the OLT is mainly focused on a centralized upstream transmission control and statistics collection modules. Consequently the OLT node model comprises an upstream receiver, the OLT process module, the upstream packet sink and a downstream transmitter. As shown in Figure 3-3, the bus receiver block, Up_Rx, receives and later applies the upstream packets into the OLT process module, OLT_process, programmed to define the node data processing principles. In that sense if a received packet represents upstream traffic, it would be used by the process module to draw instant performance characteristics, such as the channel throughput and packet delay, before it proceeds to the standard OPNET sink block, “Up_sink”, and the whole process terminated by discarding the received packet.

In contrast, if a packet represents a report message, used by an ONU to inform the OLT about its buffer queuing status, the relevant information is extracted by the OLT process module to generate a grant message according to the incorporated MAC algorithm. Produced grant messages are then broadcasted using the standard OPNET bus transmitter, Down_TX, to the corresponding ONUs.

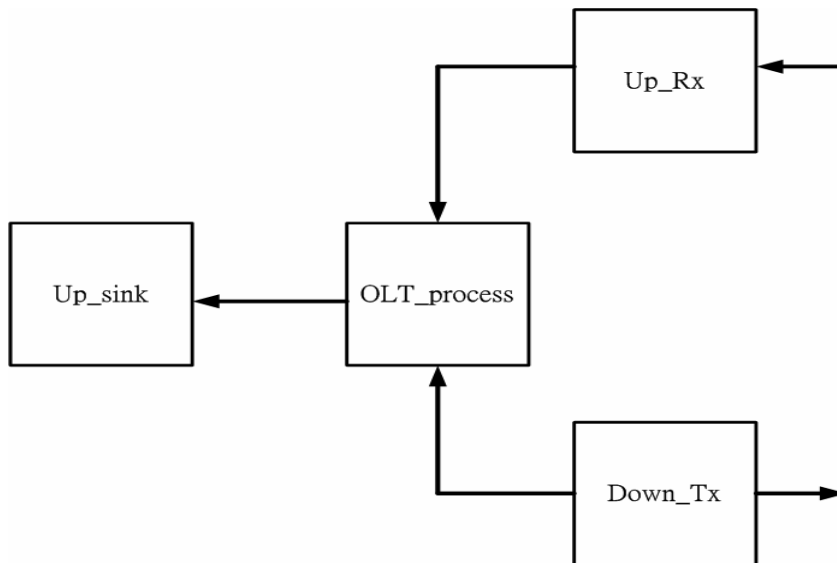


Figure 3-3 OLT Node model

In the node model, the detail underlying operation principle of the OLT process module is patterned with the help of the OPNET process editor taking into consideration the applied MAC algorithms. To evaluate network performance under different MAC protocols, which is the aim of the research in this area, just the OLT process module is required to be modified in the OPNET process domain to account for the resource allocation principles of the various algorithms.

3.3.1 OLT Process Module

The OLT process module shown in Figure 3-4 demonstrates the state transition diagram of the OLT node, representing its operation under the control of various MAC algorithms. It comprises an initial state, “Init”, a packet processing state, “pk_proc”, an idle state, a grant message processing state, “grant_proc” and a transmission state, “TX” in agreement with the main functionalities of the OLT node model described above.

The initial state is executed at the beginning of each simulation to initialize the network variables, such as the data rate, frame size or number of ONUs in the

PON. Subsequently the process model stays idle until an event has occurred. When for example an upstream packet arrives, the model will move from the idle state to the pack process state where the received packet is analysed and the information carried is processed depending on the MAC protocol principles. To deal with individual operations, triggered by the arrived of report packets, such as network resources allocation methodology and the generation of grant messages, the operation state will have to switch to the “grant_proc” state to arrange the upstream time-slots. These whole processes are controlled and defined by using C programming. Once the grant messages are produced, a self-interruption is triggered to transmit these grant messages to ONUs at the “TX” state.

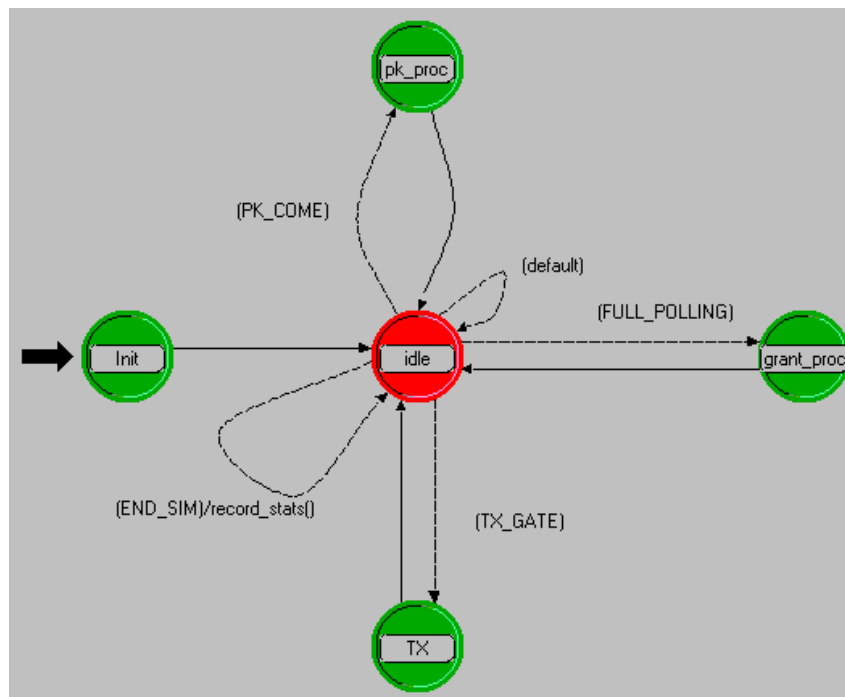


Figure 3-4 State transition diagram of the OLT process model

3.4 ONU Node Model

Similar to the OLT node mode, the ONU node model also contains a transceiver module, the processor module and a sink module to receive, transmit and process packets. Furthermore, as shown in Figure 3-5, with the intention of generating and buffering upstream data, the ONU node model displays two additional function

modules known as the upstream traffic source, Up_source, to generate upstream data and the first-in-first-out queuing buffer, Queue_buffer, to buffer data until the assigned upstream time period is located, respectively. In relation to the simulation traffic characteristics, different traffic types, such as self-similar or Poisson distributions can be easily generated by using the standard traffic generation model in the OPNET library. When the ONU receives the assigned grant message from the OLT, the message information is extracted and arranged according to the deployed MAC protocol in the ONU process module. Once the upstream transmission cycle time reaches the assigned upstream time-slot, the ONU process module will record the buffer queuing status into a report message which is then transmitted with the queuing data at the assigned time-slot.

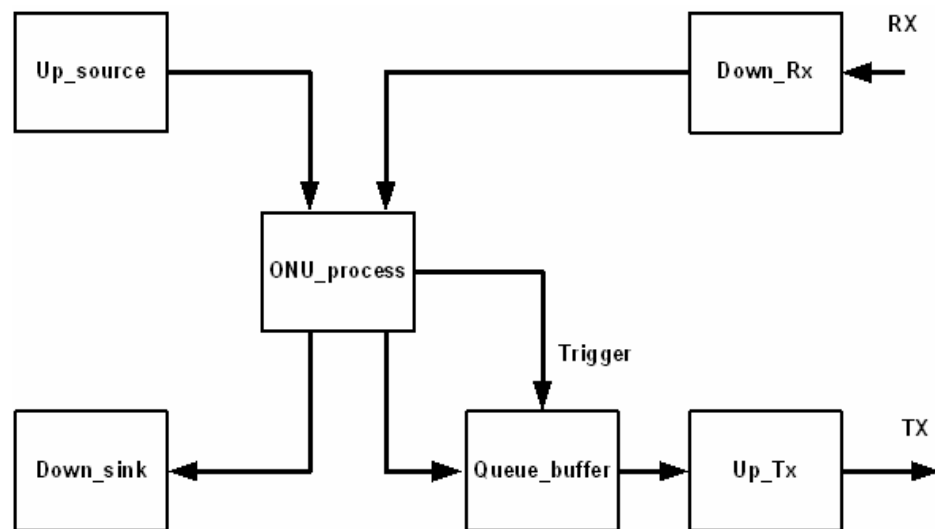


Figure 3-5 The ONU node model

3.4.1 ONU Process Module

The state transition diagram of the ONU process module is shown in Figure 3-6. In the initial state, “init”, the configuration of each ONU node and the registration of ONU specifications are obtained. While active, three main network processes take place according to the order of events. In the event of an upstream packet delivery, the process state moves from idle to the upstream data process state,

“fr_src”, in order to store or discard the upstream packet according to the ONU buffer queuing status, returning at the end of the process back to idle. If the packet arrived at the buffer is the assigned grant packet, the process state will move to the grant packet process state, “GPK_proc”, to extract the upstream time-slot window. Finally, as soon as the transmission cycle is in close proximity of the assigned upstream time-slot, the process is self-interrupted to switch to the report packet generation state, “gen_RPT” to store the ONU buffer queuing status information in a report message and consequently transmit it through the self-triggered transmission state, “TX”, concurrently with the upstream data.

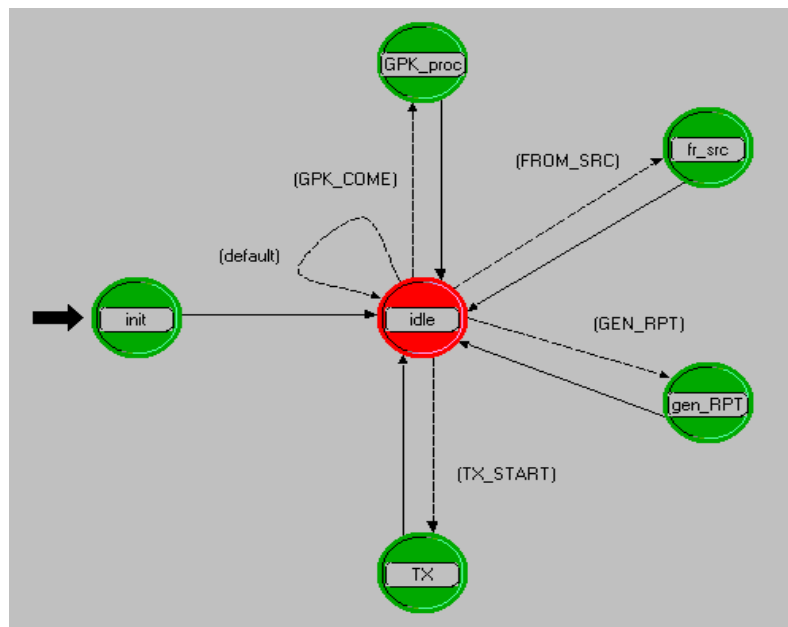


Figure 3-6 State transition diagram of the ONU process model

3.5 Simulation Test Bed

To present a valid assessment of the developed models, the simulation results drawn by the application of the IPACT algorithm were compared and contrasted to the performance measures presented in literature. Taking into consideration that IPACT has been devised for EPON applications, a design methodology was pursued that would initially process the network models to demonstrate EPON operation, record the network performance, edit the network models to simulate a

GPON logical topology and weigh the recorded results against the former traces to present for the first time a direct evaluation of a given protocol performance in view of the two increasingly deployed, highly competitive access technologies. Reprogramming between EPON and GPON logical operation would require the accurate computation of ONU upstream time-slot transmission by classifying the values of maximum polling cycle time, guard time between two upstream time-slots, and RTT which are per standard defined [23, 28].

In a TDM-DBA algorithm, the maximum polling cycle time denotes the longest period of time that each ONU needs to wait before being provided access. If the cycle time is prolonged, it would provide increased delay for all packets, including time sensitive packets. On the other hand, a short cycle time would imply more unused bandwidth which in conjunction with a constant guard time, as will be explained later is expected to decrease channel utilisation rate. To optimise between the network packet delay and utilisation rate, the maximum polling cycle time has been set to a typical 2 ms [137, 138] which is utilised in most of published TDM-DBA protocols.

In establishing and terminating communication between the OLT and each ONU, every transceiver takes time to turn on or off, implying the requirement of a vacant time interval known as the guard time to synchronise packet transmission in the form of defining initiation of burst mode operation [9] and provide a safe guard for distorted signals. Although a typical value of the guard time suggested in EPONs is 1 μ s [75, 84, 139], IPACT has considered a 5 μ s figure to display a worst case scenario. In addition, a characteristic particularly important in time-slot allocation in GPONs, instead of a sole, fixed aggregate data rate specified in EPONs, multiple data rate operation should be displayed in GPONs which practically would require transition between guard times to match each transmission speed [27]. As shown in Table 3-1, the overall guard time in GPONs, presented as “Total Time” in the table, defined as the summation of the parameters, preamble time, delimiter time and “Guard Time” which is different

with the guard time in EPON. The parameter, “Guard Time”, in GPONs is employed to turn on or off the transceivers.

Table 3-1 Recommended allocation of burst mode overhead time for OLT [27]

Upstream Data Rate (Mb/s)	Total Time (bits)	Guard Time (bits)	Preamble Time (bits)	Delimiter Time (bits)
155.52	32	6	10	16
622.08	64	16	28	20
1244.16	96	32	44	20
2488.32	192	64	108	20
Notes	Mandatory	Minimum	Suggested	Suggested

Having set an appropriate guard time, the RTT should be critically considered to ensure each upstream packet from ONU_i reaches the OLT exactly at the end of its specified RTT time and accordingly the first packet from the following ONU, ONU_{i+1} will reach the OLT with only a guard time interval delay with respect the last bit of information from ONU_i . The employed RTT is calculated by taking the OLT and ONU signal processing times, T_s , and optical fibre propagation delay, T_{pd} , into consideration. The optical fibre propagation delay is determined by the distance between two transceivers, while the signal processing times in each ONU and the OLT account for optical to electronic and electronic to optical signal conversion times, T_{oe} & T_{eo} , specified in the GPON standard to equal $(T_{oe} + T_{eo} + 2 \times T_s)$ with a maximum value of less than $50\mu s$ [28]. Table 3-2 summarises the individual maximum polling cycle time, guard time and RTT, employed to distinguish between the EPON and GPON network models over which the IPACT protocol has been applied to perform dynamic bandwidth allocation.

Table 3-2 IPACT modelling environments [28, 138]

	EPON	GPON
Maximum polling cycle time	2ms	2ms
Guard time	5 μ s	96 bits for 1.24Gbit/s 192 bits for 2.48Gbit/s
RTT	200 μ s for 20 km	300 μ s for 25 km

3.5.1 EPON Modelling and Simulation Results

The IPACT protocol has considered various bandwidth arrangement mechanisms to satisfy escalating network performance. To that effect, a mechanism called limited service algorithm has presented slightly increased performance in comparison to others by means of averaging the network capacity among ONUs and as a result provided fair queuing among ONUs in the EPON modelling [104]. According to the algorithm each ONU is assigned to a maximum guaranteed bandwidth and naturally if the bandwidth demand from an ONU is less than the allocated figure, the OLT will have satisfied the requirement fully. Otherwise, the ONUs with increased demand will have suffered a limited service restricted in all cases to a constant maximum [85].

To abide by the EPON standard, the OPNET editor comprises a single OLT and 16 ONUs with 1Gbit/s aggregate data rates available for both upstream and downstream transmissions for link lengths up to 20 km [138]. In addition, as described in section 3.5, a 2 ms maximum cycle period, 5 μ s guard time, 25 μ s OLT and ONU signal processing times and 15 kbytes maximum transmission window are employed to contrast the network performance characteristics achieved with the developed simulation testbed, with the published IPACT figures [85]. Significantly, network traffic is generated based on a Pareto self-similar traffic model with typical Hurst parameter 0.8 since from the point of view of increased accuracy as comparable possible to a real deployment [85, 138]. The

maximum ONU channel capacity is set to 100 Mbit/s to effectively simulate the bandwidth requirement of representative network services of the short-term future [80, 87, 115].

The recorded channel throughput and mean packet delay versus network offered load are shown in Figure 3-7 and Figure 3-8 respectively. It is important to note that since IPACT assigns transmission timeslots to each ONU right after the OLT receives their bandwidth requirement, individual grant signals downstream are communicated in parallel with ONU upstream data transmission, suggesting that individual ONU RTT does not result in unused time-slots at heavy network traffic. As a result, the main factors to affect the maximum channel throughput in use of the IPACT protocol are the adjacent ONU guard time adding up in each polling cycle to a total of 75 μ s ($15 \times 5 \mu$ s). This gives rise to approximately 4% unused upstream time-slot length in each polling cycle. Additionally, only a fraction of the assigned bandwidth is fully utilised taking into consideration the aggregate network transmission rate and the unused time-slots resulting to around 950 Mbit/s maximum channel throughput as indicated by Figure 3-7 matching closely the reported IPACT figure [85].

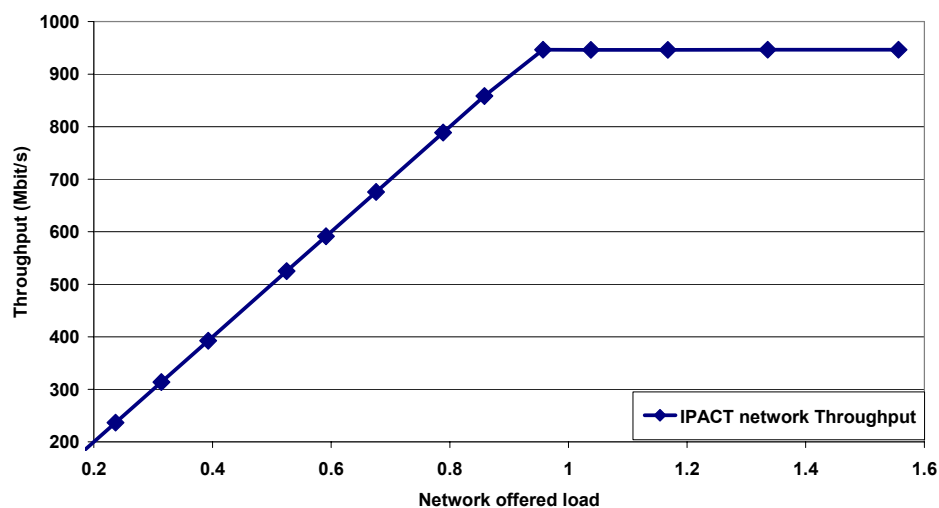


Figure 3-7 IPACT network throughput in EPON

Figure 3-8 presents the simulated mean packet delay performance alongside a reproduced trace based on approximate offered load, packet delay values from literature [85]. It can be observed that the simulated trace follows quite closely the duplicated plot in both high and low ONU offered load regions except in the offered load region between 0.44 and 0.6 representing 70% to 96% of the maximum network capacity. Due to a fact that if the overall network loading exceeds the capacity, the surpassed upstream packets have to wait and accumulate at the buffer. In that sense, when the network loading surpasses the network capacity, an significantly increasing in packet delay should be presented at the simulation results, so the simulated values are more reliable [84, 110, 111, 113].

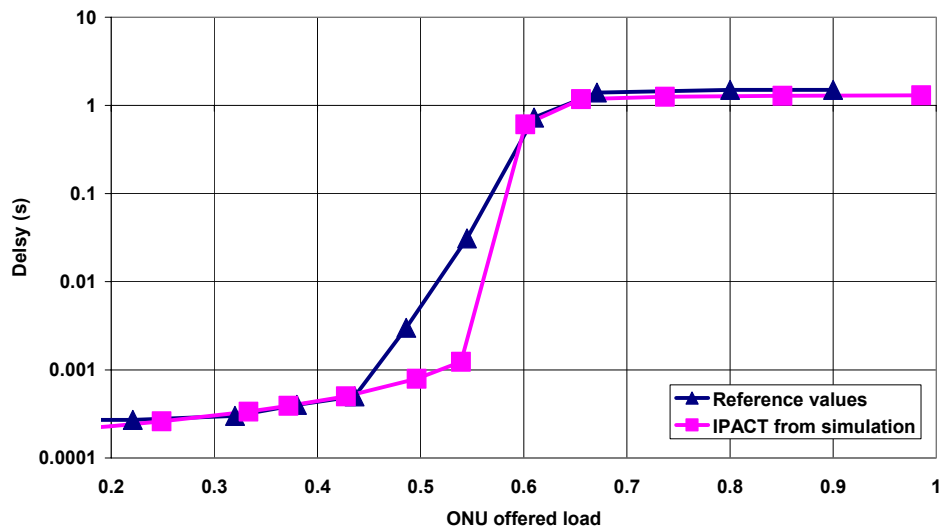


Figure 3-8 Simulated packet delay performance and the reported IPACT figure [85]

3.5.2 GPON Modelling and Simulation Results

To migrate from the EPON project editor to a GPON equivalent platform, the data frame formats, and the transmission mechanism of the grant and report messages between the OLT and ONUs would have to be revised in the OLT and ONU process models respectively using the parameter values presented in appendix A for GPON [26, 28, 88, 139]. Naturally data in GPON networks is transmitted in the form of GPON packets while the report messages or so called dynamic bandwidth report upstream (DBRu) are communicated at the beginning of each

dedicated upstream time-slot rather than the end in EPONs. Similarly, the grant messages in EPONs can be transmitted at any instant during a polling cycle, while the so called upstream bandwidth maps (US BW Maps) in GPONs need to be transmitted only at the beginning of each polling cycle [28]. In the sense, the grant message in GPONs will arrive each ONU latter than in EPON causing a slightly longer packet delay and less channel throughput, but the QoS and SLA can be further enhanced in GPONs by concerning all of the bandwidth requirements in a polling cycle into DBA protocols.

For the evaluation of the GPON simulation set-up in the presence of the same IPACT algorithm used over the EPON editor, 16 slightly reconfigured ONUs are connected to access a total of 1 Gbit/s aggregate data rate pipeline ranging up to 25 km [27]. In addition, a 2 ms maximum cycle period, 96 bit guard time and 25 μ s OLT and ONU signal processing time are set according to the GPON standards ITU-T G.984.3 and G.984.2 [27, 28]. To accurately contrast the protocol performance over the two standards, the maximum ONU upstream transmission window, maximum ONU channel capacity and network traffic model have remained the same, still within specifications of a GPON topology.

As shown in Figure 3-9 and Figure 3-10, the characteristics of the network throughput and mean packet delay versus network offered load performance recorded for the GPON network model are significantly similar to the performance measures of EPON. In consideration of QoS and SLA, the OLT in the GPON network cannot transmit any upstream bandwidth maps for ONUs until all of the report messages from ONUs are collected. In that sense, if the signal propagation time from the OLT to the first ONU is longer than the upstream transmission period of the last ONU, parts of the upstream time-slots will stay idle and will not be used for data transmission. As a result, to include QoS and SLA into a DBA protocol, the supported maximum network throughput and mean packet delay in the GPON model are slightly worse than in the EPON model. Nevertheless, the similar characteristics of network performance have proven the possibility of directly applying the EPON algorithms to allocate bandwidth in

GPON architectures by readjusting the data frame formats and the time to communicate grant and report messages between OLT and ONUs.

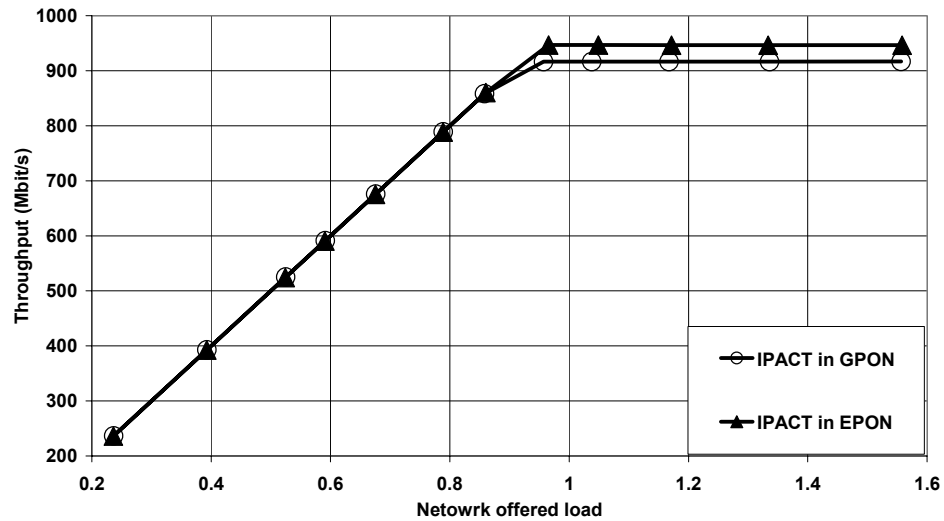


Figure 3-9 IPACT network throughput in EPON and GPON models

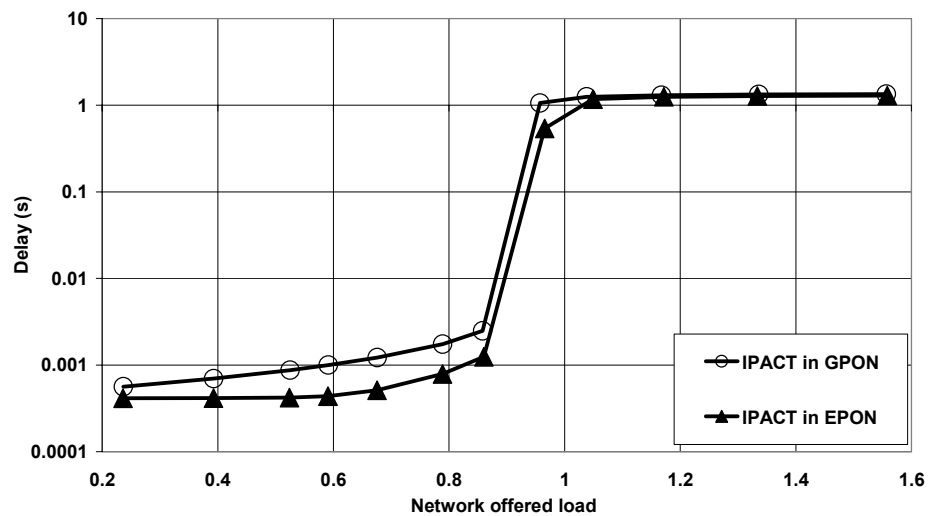


Figure 3-10 Mean packet delay for IPACT in EPON and GPON models

3.6 Summary

The industrial standard network simulation software, OPNET Modeler, has been used in this chapter to develop a GPON model for the implementation of the proposed DBA protocols presented in successive chapters. OPNET allows users

to employ already existing libraries of commercialised network elements such as transceivers and extensive traffic models. This speeds up the modelling implementation process dramatically, while offers confidence and research output value since practical simulations representing closely real conditions can be performed. Subsequently characteristics of channel throughput, packet delay or buffer size under heavy or low network loading conditions can be obtained with no limitations. Equally important, once a simulation platform for a specific technology has been constructed modifications of network conditions or evaluation of different algorithms becomes straight forward, since it requires simply the adaptation of the OLT and ONU process models to reflect the corresponding algorithms and the complete re-utilisation of the node and network modules.

To verify the developed OLT and ONU modules, a well known TDM-DBA protocol, IPACT, is implemented in the EPON and GPON simulation models. Although IPACT is intended for EPON applications the interleaved polling scheme is successfully applied to allocate bandwidth in GPON architectures, being also of tree topology, by redesigning the frame format and readjusting the time to transmit the grant and report messages between the OLT and ONUs. In this experiment, the characteristics of channel throughput and packet delay under heavy and low network loading conditions are obtained to evaluate the accuracy of the EPON and GPON models. In addition, the observed resemblance in bandwidth utilisation efficiency when arranging upstream bandwidth in both models has establishing the validity of employing IPACT as a reference for assessing the developed GPON protocols.

Chapter 4

Dynamic Minimum Bandwidth Allocation Protocol in GPONs

Following an analysis of the most significant TDM-DBA protocols proposed to date, an original algorithm is described in this chapter to overcome existing limitations and improve network performance figures. In that direction the newly-developed GPON simulation platform presented in chapter 3 is employed to evaluate what is known as the “Dynamic Minimum Bandwidth” scheme designed to demonstrate diverse service level servicing for ONUs by means of individual guaranteed bandwidth and buffer queuing status.

4.1 Introduction

Current TDM-MAC protocols can be classified as either static or statistical, corresponding to constant and dynamic bandwidth allocation protocols respectively [31, 92, 93, 97, 108, 114]. The former always assign each ONU a constant time-slot for transmission without taking into consideration the bandwidth requirement, SLA and QoS. As a result they have been widely discarded for use in next generation PON standards due to their inefficient bandwidth utilisation rates [81]. In contrast, the latter employ in general more attractive features to support enhanced bandwidth utilisation, providing reasonable QoS but for distinctive services [88-91]. To enhance QoS to accomplish FSANs, multiple aggregate data rates have to be supported by new generation protocols [27] allowing ISPs to assign customers multiple service levels according to customers’ requirements [140].

An innovative DBA protocol has been developed in that direction, to demonstrate three different types of service levels. Depending on each ONU service level, the algorithm would initially assign a corresponding “guaranteed minimum bandwidth” to satisfy their basic service requirement according to the overall network capacity. Subsequently the OLT would assign any “unused bandwidth” from the initial allocation process to ONUs on demand, according to their buffer queuing status. Following variations to the network capacity, the OLT would be capable of readjusting the “guaranteed” and “unused” bandwidths among ONUs to comply with subscriber contracts.

To evaluate the modelled network performance in view of the proposed protocol, the developed algorithm was set to define the OLT process model in OPNET alongside the algorithms of published protocols, possible since the simulation GPON platform has been demonstrated to accomplish similar performance to literature. The simulation figures have been assessed in the presence of realistic patterns of network traffic in terms of packet delay and channel throughput.

4.2 Development of a DBA Protocol

In the majority of TDM-DBA algorithms, local traffic is classified into high, medium, and low priorities to access the network according to time-sensitiveness. When the OLT receives bandwidth requirement reports from ONUs, it firstly distributes upstream bandwidth to satisfy high priority traffic, subsequently assigning the remaining bandwidth to medium and low priorities. This priority method is particularly useful in FTTB or FTTC architectures where multi-subscribers with various service levels share the resources of a single ONU [14, 113] and each report message only contain the summation of subscribers’ bandwidth demands in an ONU. As a result, the OLT needs to consider each ONU equally, representing the same service level. Nevertheless, to provide triple-play services in a full service access network, the SLA should be considered in

bandwidth arrangement [81]. To match that sense, the SLA has been taken into consideration in the developed DMB protocol based on FTTH architecture with an attempt to dynamically provide more bandwidth for the higher service level subscribers than for their lower counterparts to demonstrate network integrity and QoS according to maximum network capacity, subscribers' buffer queuing status and service levels. In addition, the number of ONUs active in a network at a given time usually varies, the amount of assigned bandwidth for active ONUs should be dynamically increased to fully utilise surplus capacity. Hence, the ability to automatically adjust the guaranteed minimum bandwidth in each polling cycle becomes one of the main characteristics of the DMB algorithm.

Practical networks, as a result of the development and variety of services, demonstrate increasing disparity in network usage, directing ISPs to provide multiple service plans to accommodate clients' choice [140]. Accordingly the monthly rental for exalted service level subscribers should be higher than their lower counterparts, allowing them in parallel high priority in accessing the network. To accommodate this characteristic, DMB development should combine multiple service level provision with diverse priority in accessing the network. This has been achieved in the proposed algorithm by the introduction of a parameter expressed by "*weight*" [106, 110]. To adjust the guaranteed minimum bandwidth in conjunction with the *weight* parameter, the overall network bandwidth is apportioned into several small segments, and subsequently individual active ONUs can be assigned a number of these segments according to their *weight*. With the intension of simulating practical network conditions, *weight* values are selected in order to comply with the NTT VDSL service plan corresponding to 50, 70 and 100 Mbit/s provision for service levels with *weight* 2, 3, and 4 respectively [140].

4.2.1 The Bandwidth Allocation Mechanism

According to the Dynamic Minimum Bandwidth (DMB) algorithm, the available service levels are denoted by t and the corresponding *weight* parameters by W_t . As a result, service level one, for example, will acquire the lowest *weight* which reflects the amount of occupied time-slots in one polling cycle.

To dynamically assign network capacity among ONUs, transmission time-slots for each client are allocated in two stages. In the first stage, a guaranteed minimum bandwidth, B_{min}^t , is assigned to each ONU according to the network capacity and ONU's service level to satisfy the relative service requirements. In the second stage the unused bandwidth among ONUs will be dynamically adjusted according to their requirements in bandwidth. In particular, to provide diverse service levels and to be able to adapt to variable data rates, the guaranteed minimum bandwidth, B_{min}^t , should be defined as the summation of two parameters: a basic bandwidth, B_{basic} , and an extra guaranteed bandwidth, B_{ex}^t . Henceforth, the guaranteed minimum bandwidth for service level t is given by:

$$B_{min}^t = B_{basic} + B_{ex}^t . \quad (4-1)$$

In eq. 4-1, the basic bandwidth, B_{basic} , represents a constant bandwidth available to all ONUs independently of service level, utilised to support the basic network services. In a FSAN, the suggested bandwidth for an ONU is 73 Mbit/s which can be used to support three HDTV channels (3*20 Mbit/s), internet access (10 Mbit/s), video conference (2 Mbit/s) and telemetric/remote control (1 Mbit/s) [14, 15]. Since subscribers only use one HDTV channel at a time, the basic bandwidth can be set to 33 Mbit/s to fulfil the bandwidth requirement of a single HDTV channel and other suggested services. In order for the OLT to fully use the network capacity and dynamically assign more bandwidth to higher service level ONUs at variable data rates, the extra bandwidth parameter, B_{ex}^t , is included in the calculation of B_{min}^t . For service level t , the extra bandwidth, B_{ex}^t , is assigned by considering the summation of the basic bandwidth subtracting from maximum

network capacity B_{total} and the ratio of weight between service level t and the sum of each active ONU given by:

$$B^{t}_{ex} = (B_{total} - k \times B_{basic}) \frac{W_t}{\sum_{t=1}^3 W_t N_t}, \quad (4-2)$$

where k is the number of active ONUs and N_t is the number of active ONUs in service level t .

Statistically, only a fraction of ONUs use their entire guaranteed minimum bandwidth in each polling cycle. The algorithm in the second stage will proportionally assign the unused bandwidth to ONUs whose requirement exceed their assigned guaranteed minimum bandwidth, B^{t}_{min} , calculated in stage one. With the intention of flexibly arranging the unused bandwidth, the OLT needs to calculate the unused, B_{unused} , and excess bandwidth requirement, B_{ex_need} , and then proportionally assign the unused bandwidth. The unused and excess bandwidths in a polling cycle can be calculated by subtracting the corresponding ONU queuing length from the guaranteed minimum bandwidth and the guaranteed minimum bandwidth from the ONU queuing length, as shown in eq. 4-3 and eq. 4-4 respectively.

$$B_{unused} = \sum_{i \in k} B^{t}_{min} - R_i \quad , \text{ if } B^{t}_{min} \geq R_i ; \quad (4-3)$$

$$B_{ex_need} = \sum_{i \in k} R_i - B^{t}_{min} \quad , \text{ if } B^{t}_{min} < R_i , \quad (4-4)$$

where R_i is the queuing length of ONU _{i} .

After the OLT has received the entire queuing information, it would have to divide the unused bandwidth to satisfy the extra requirements among ONUs. The amount of the extra assigned bandwidth per ONU, $B^{i}_{ex_assigned}$, is given by the ratio of the extra required bandwidth, $B^{i}_{ex_required}$ for that ONU and the total extra bandwidth requirement in the network, multiplied by the total unused bandwidth from the first stage, as shown in eq. 4-5 and eq. 4-6

$$B_{ex_assigned}^i = B_{unused} \times \frac{B_{ex_required}^i}{B_{ex_need}}; \quad (4-5)$$

$$\text{where } B_{ex_required}^i = R_i - B_{min}^t. \quad (4-6)$$

Finally, the maximum allocated bandwidth $B_{max_allocated}$ for ONU_i will be equal to the summation of B_{min}^t from stage one and $B_{ex_assigned}^i$ from stage two. Otherwise if ONU_i 's request for bandwidth is smaller than the total, the allocated bandwidth, $B_{allocated}^i$ will be equal to R_i as given below:

$$B_{allocated}^i = \min \left(\begin{array}{l} B_{min}^t + B_{ex_assigned}^i \\ R_i \end{array} \right). \quad (4-7)$$

To summarise the attributes of the algorithm, the assigned guaranteed minimum bandwidth for each ONU is dynamically adjusted according to ONUs service levels and network capacity and then the unused bandwidth in each cycle is proportionally allocated to ONUs according to their buffer queuing status. In the mechanism, the OLT can subsequently automatically adjust the assigned bandwidth per ONU to support QoS and SLA according to aggregate network data rate and ONUs' queuing status aiming to assign more bandwidth to higher service level subscribers and consequently to reduce their packet delay compared to their low service counterparts. As a result, ISPs can provide customers with various service levels in a straightforward manner and simply upgrade the network provision in increased aggregate rates without modification of the MAC protocol.

4.3 The DMB Model Implementation and Analysis

To evaluate the performance of the proposed scheme, a GPON network has been devised in OPNET modeller, comprising a single OLT and 16 ONUs with varying weights representing different service levels at the upstream transmission of 1 Gbit/s for link lengths up to 25 km [27]. In addition, a 2 ms maximum cycle

period and 96 bits guard time are chosen to establish data transfer between the OLT and ONUs in order to offer a comparable platform with published algorithms [75, 86, 110, 111]. Network traffic is generated, based on a Pareto self-similar traffic model with typical Hurst parameter of 0.8 to provide increased accuracy with regards to real deployments [85, 138]. The maximum ONU channel capacity and the basic bandwidth, B_{basic} , are set to 100 Mbit/s and 33 Mbit/s respectively to effectively simulate the requirement in bandwidth of representative NTT VDSL network services as previously explained.

In practical networks, the number of end users subscribed to high service plans is currently lacking low service plan provision. Therefore, the proportion of subscribers in each service level from high to low is set to 1: 5: 10, in the first simulation scenario.

Furthermore, with the intention of examining the algorithm to resourcefully assign bandwidth when the number of ONUs in each service level is changed. A second simulation scenario has been devised by which the proportion of subscribers assigned to each service level, from high to low has been extensively changed from 1:1:14 to 1:5:10, 1:8:7, 4:5:7, 7:2:7, 10:2:4 and 14:1:1.

Finally, to confirm the ability of the algorithm to dynamically arrange any unused bandwidth from stage one to ONUs with increased requirement, the number of ONUs in each service level has been set from high to low to 2, 6 and 8, with half of ONUs in each service level operating at 33 Mbit/s fixed traffic loading, while the remaining experiencing gradual increments in traffic load.

4.3.1 Simulations and Performance Analysis

In the first simulation scenario, the characteristics of channel throughput versus network load for IPACT and DMB schemes are shown in Figure 4-1. In order to provide a valid evaluation of the proposed algorithm's performance against IPACT, taking into consideration that the latter was intended for EPON

applications, preliminary work investigated the successful adaptation of IPACT to the GPON model as analysed in chapter 3. It has been observed that IPACT can be equally applied to EPON and GPON architectures establishing its validity as a reference for assessing the proposed scheme as clearly illustrated in Figure 3-9.

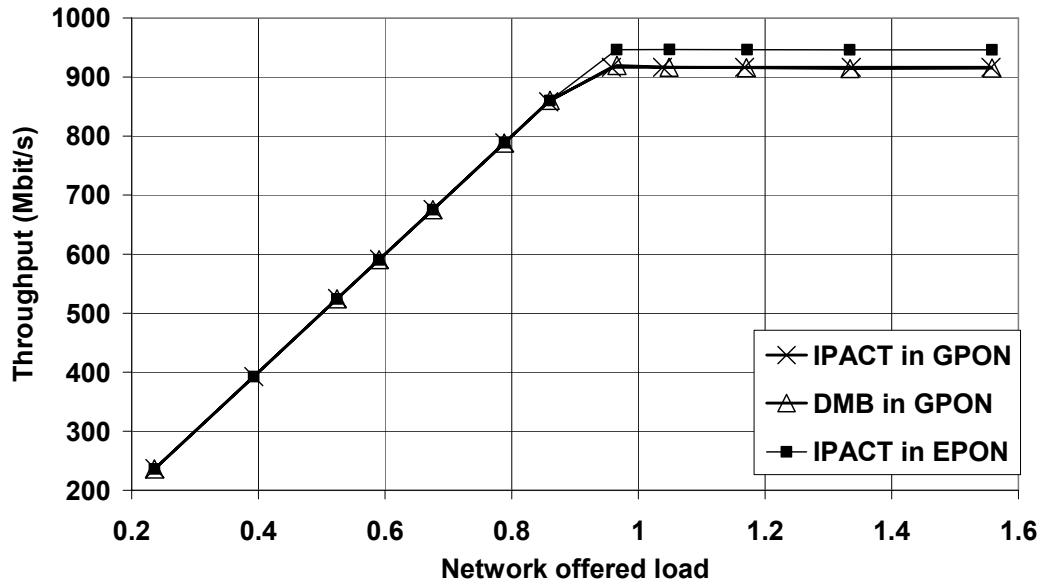


Figure 4-1 Channel throughput for IPACT and DMB protocols in GPON

Figure 4-2, however, displays a notable disparity in the simulated mean packet delay performance between the two algorithms. According to the traces, the DMB exhibits around a factor of 10 less packet delay in comparison to IPACT under high network load, demonstrating that the proposed algorithm is much more efficient in utilising the limited network capacity. This significant reduction is due to the fact that the ONUs with higher requirement in bandwidth are allocated with most of the available network bandwidth in priority when the maximum network capacity is reached. Consequently, this is expected to greatly improve the performed quality in particular in the presence of T-CONT 4 and T-CONT 3 services.

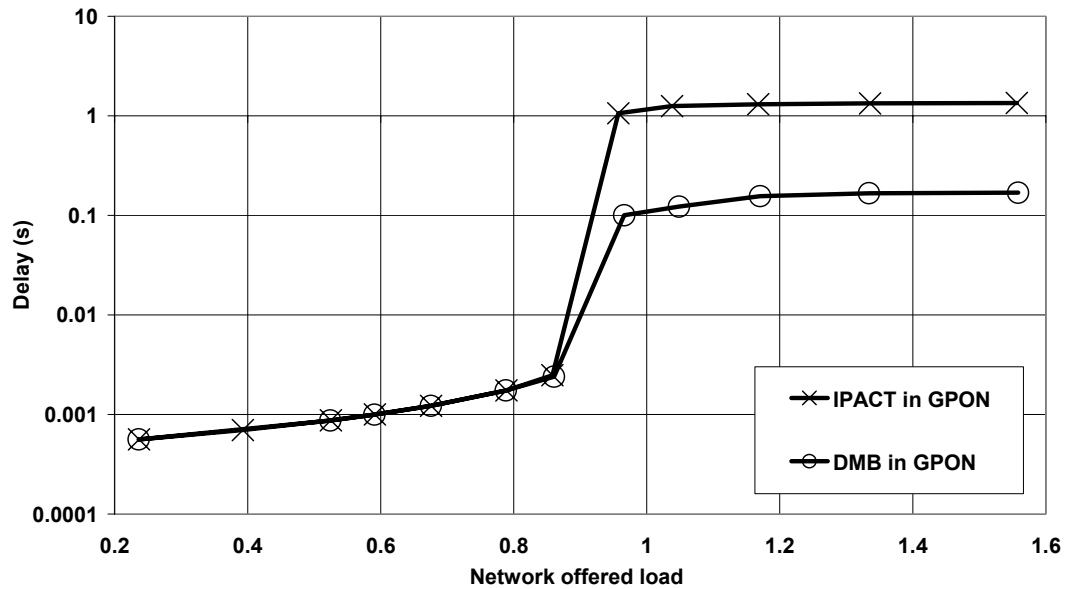


Figure 4-2 Mean packet delay for IPACT and DMB protocols in GPON

Consequently, Figure 4-3 illustrates the simulated network packet delay response for the assigned service levels. It is apparent from the plot that when each ONU's offered load is greater than half of its maximum capacity, the total user requirement in bandwidth exceeds the network capacity. Therefore, for increasing values of network load, the OLT will proportionally allocate more bandwidth among the higher service level ONUs, resulting in less packet delay for extended load figures, given by 54, 61 and 74 Mbit/s for service levels 1, 2, and 3 respectively. In addition, the measured 0.87 ms packet delay at a typical 33 Mbit/s low ONU load region allows for minimal loss and delay propagation of time sensitive applications and the accumulation of transmission time to relief congestion in the backbone network in contrast to a 5 ms maximum allowable packet delay specified in the GPON standard for T-CONT 2 services [115].

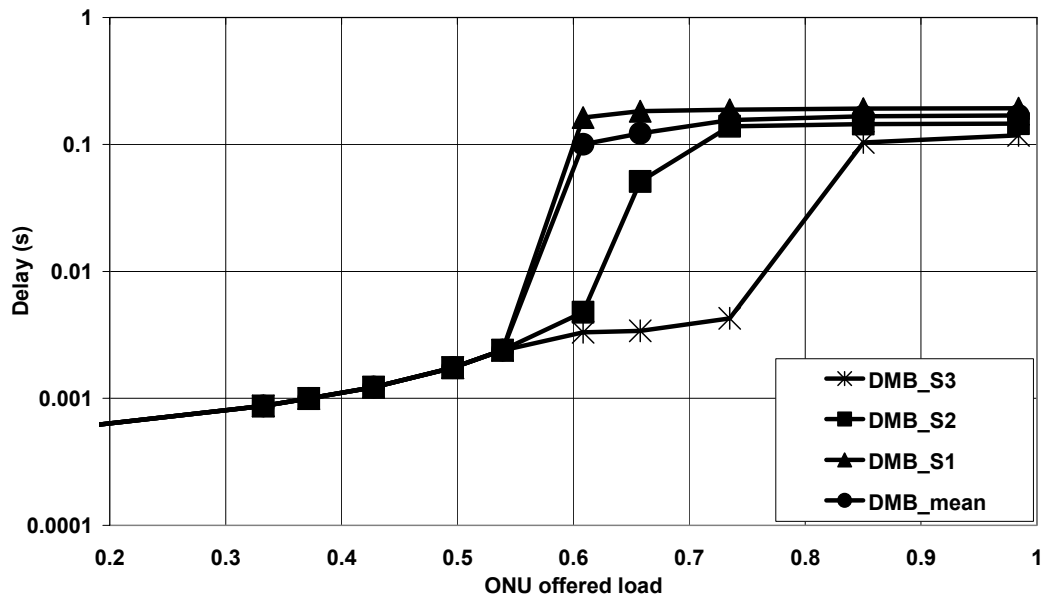


Figure 4-3 Packet delay for three service levels in DMB protocol in GPON

As suggested in the FSAN network, the maximum acceptable packet delay figures in the access network for T-CONT 2, T-CONT 3 and T-CONT 4 traffic are 5 ms, 100 ms and 500 ms respectively [115]. To provide sufficient QoS for subscribers, the maximum supportable bandwidth for time sensitive services in SL₁ ONUs is 54 Mbit/s (100 Mbit/s x 0.54) capable of providing 2 HDTV channels (40 Mbit/s), online game or education on demand (10 Mbit/s) and 4 Mbit/s for others services by using the DMB algorithm. If this is not sufficient, service levels 2 and 3 could be alternatively utilised to extend the low delay transmission bandwidth to 61 Mbit/s and 74 Mbit/s respectively. These simulation results exhibit the flexibility of the DMB protocol to embody SLA in the displayed bandwidth arrangement process.

For the purpose of analysing the performance of DMB to automatically adjust the assigned bandwidth according to SLA, the number of ONUs in each service level is varied. Figure 4-4 and Figure 4-5 demonstrate the channel throughput and mean network packet delay performance for DMB under various number of ONU utilisation for each service level. Simulation results demonstrate identical channel throughput and mean packet delay performance, independently of the assigned

percentages, confirming the ability of the protocol to maintain a steady overall network performance when the network penetration is altered by means of subscriber ratios per service level.

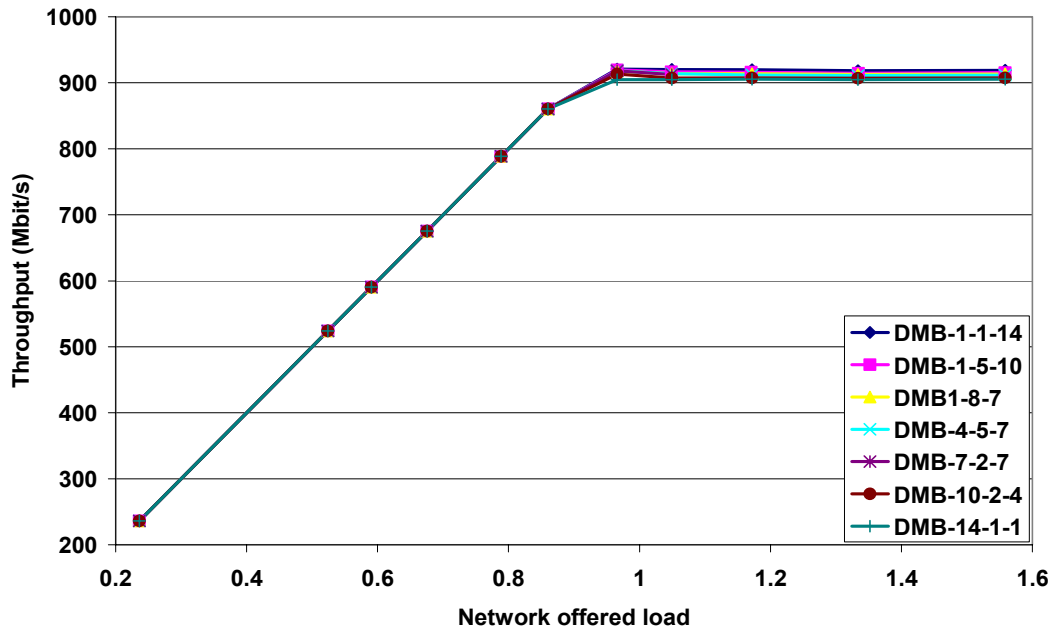


Figure 4-4 Channel throughput for DMB in GPON under various number of ONUs in each service level

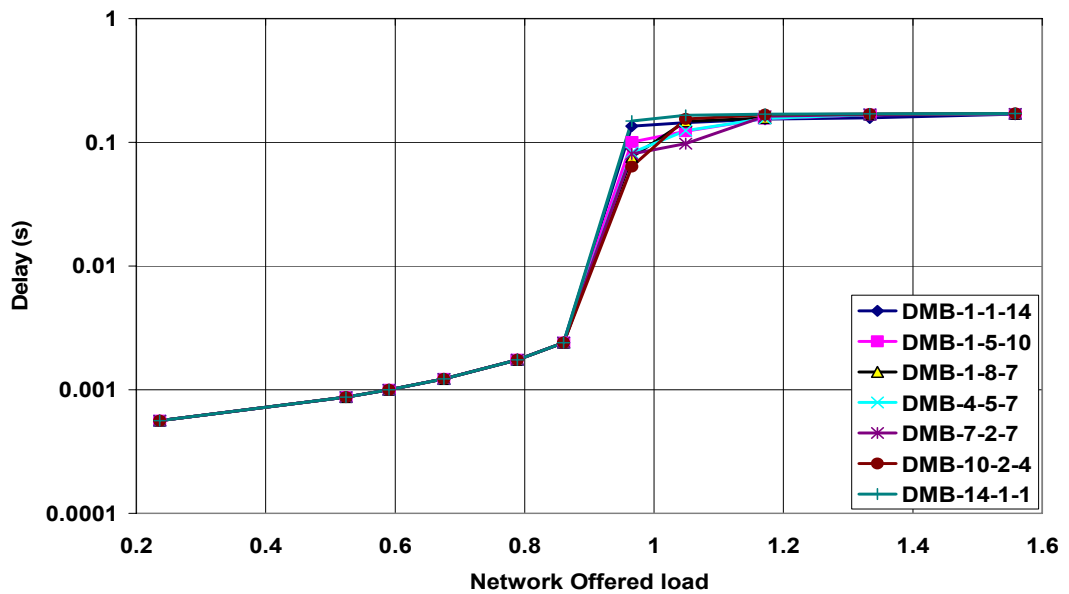


Figure 4-5 Mean packet delay for DMB in GPON under various number of ONUs in each service level

Figure 4-6 to Figure 4-12 present the detailed ONU packet delay performance for by changing the ONU quantity assigned to each service level. As presented in Figure 4-6, the first set of results represent an extreme scenario whereby single ONUs have adopted SL₂ and SL₃ provisioning while the remaining 14 are assigned to SL₁. In this scenario, the ONU packet delay performance between each level is significant different, since the weights of SL₂ and SL₃ ONUs are higher than SL₁ ONUs resulting in different assigned bandwidth in each SL ONUs. Therefore, the SL₃ ONU can enjoy better performance than their lower counterparts.

To track changes in DMB operation for varying ONU assignment to individual service levels and explore developed trends, the number of higher level ONUs is gradually increased. It becomes clear from Figure 4-6 to Figure 4-12 that the difference in delay versus ONU load between service levels is gradually reduced when the number of higher level ONUs is increased. In the excessive condition of very intensive network operation where just single ONUs operate under SL₁ and SL₂, as shown in Figure 4-12, while nearly the majority of ONUs require extensive servicing provisioning the individual ONU packet delay as expected is very similar. Nevertheless, it is guaranteed that the higher level ONUs could always enjoy less packet delay than their lower counterparts presenting the maximum 0.164, 0.198 and 0.246 second mean packet delay for service level 3, 2 and 1 ONUs respectively.

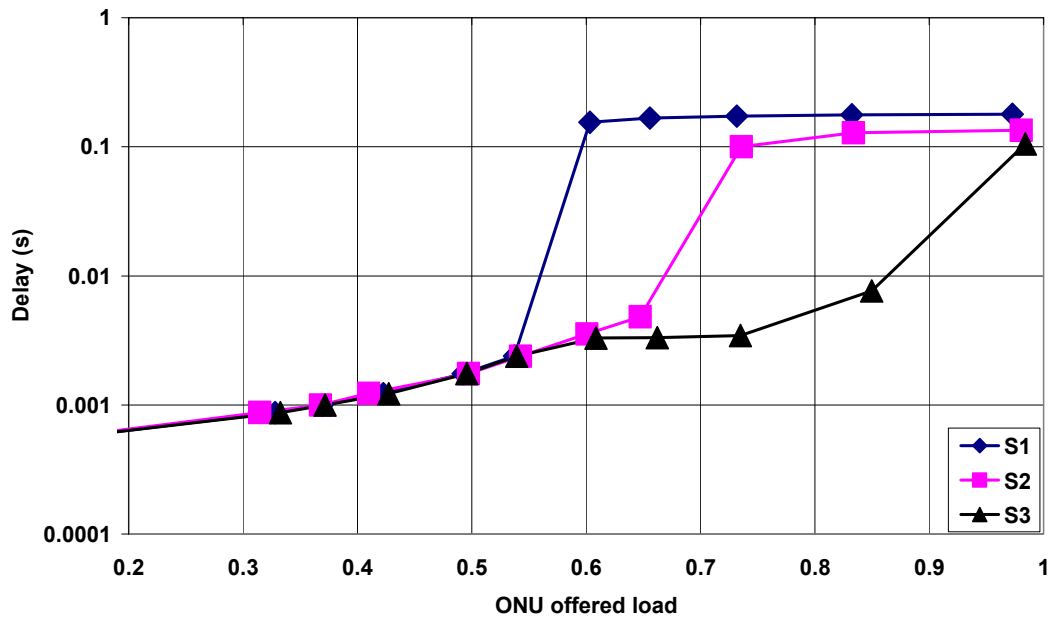


Figure 4-6 Packet delay performance for DMB in GPON when the proportional of ONU in each service level from high to low is set to 1:1:14

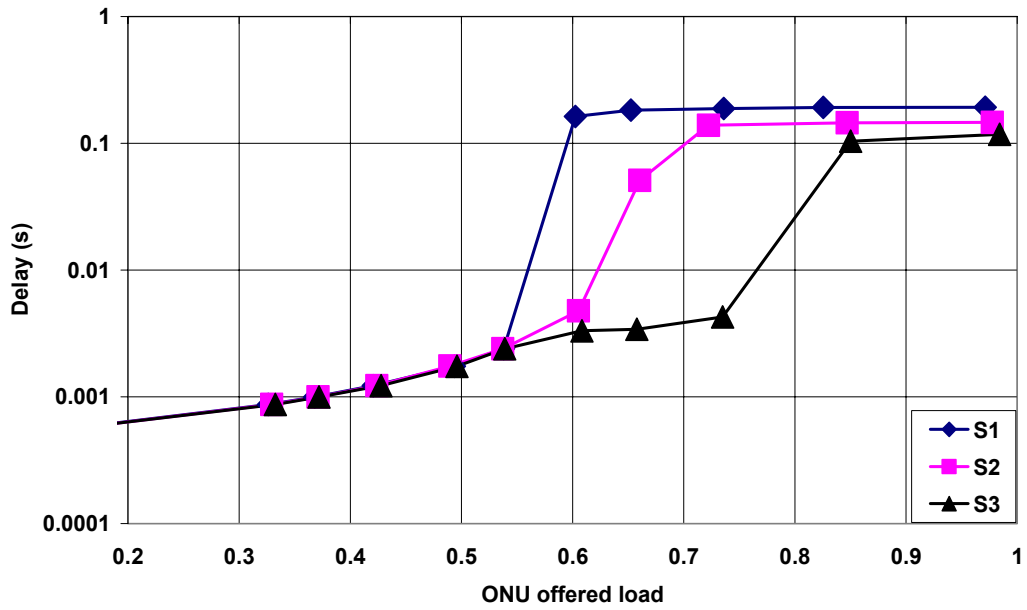


Figure 4-7 Packet delay performance for DMB in GPON when the proportional of ONU in each service level from high to low is set to 1:5:10

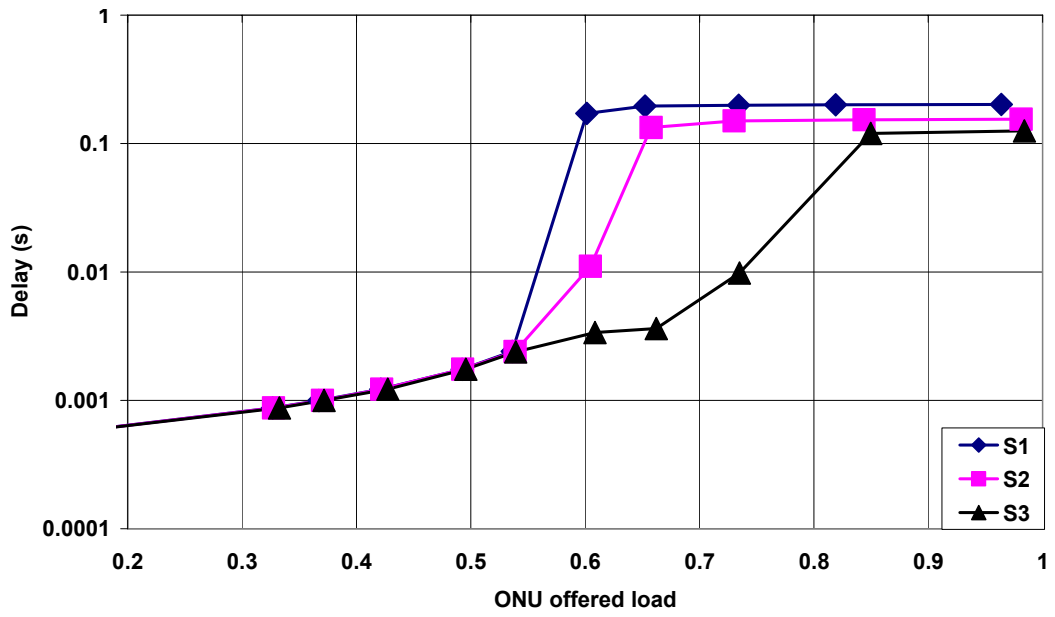


Figure 4-8 Packet delay performance for DMB in GPON when the proportional of ONU in each service level from high to low is set to 1:8:7

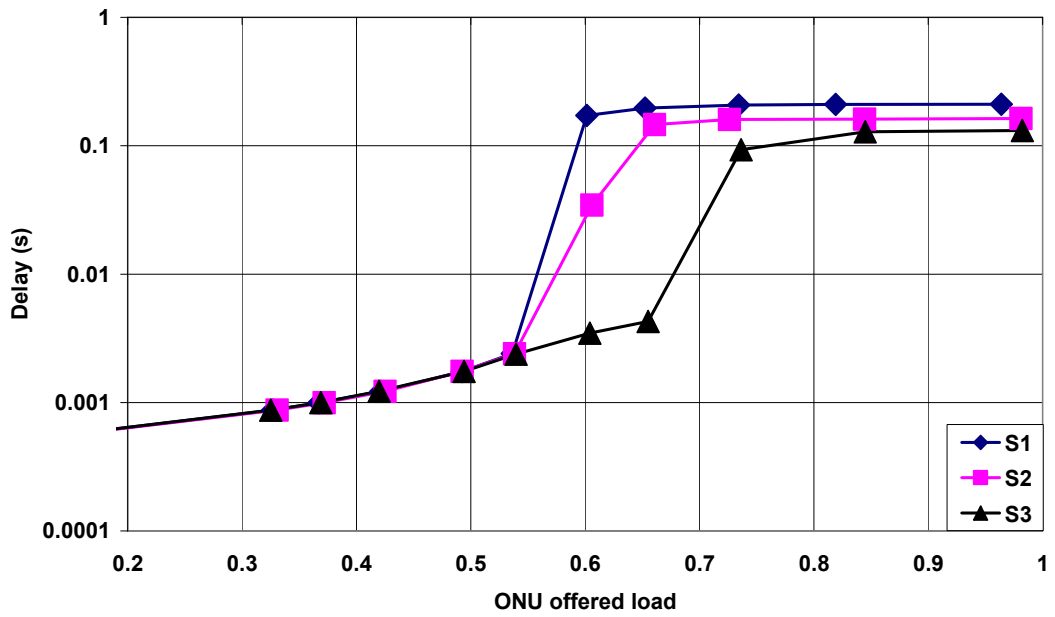


Figure 4-9 Packet delay performance for DMB in GPON when the proportional of ONU in each service level from high to low is set to 4:5:7

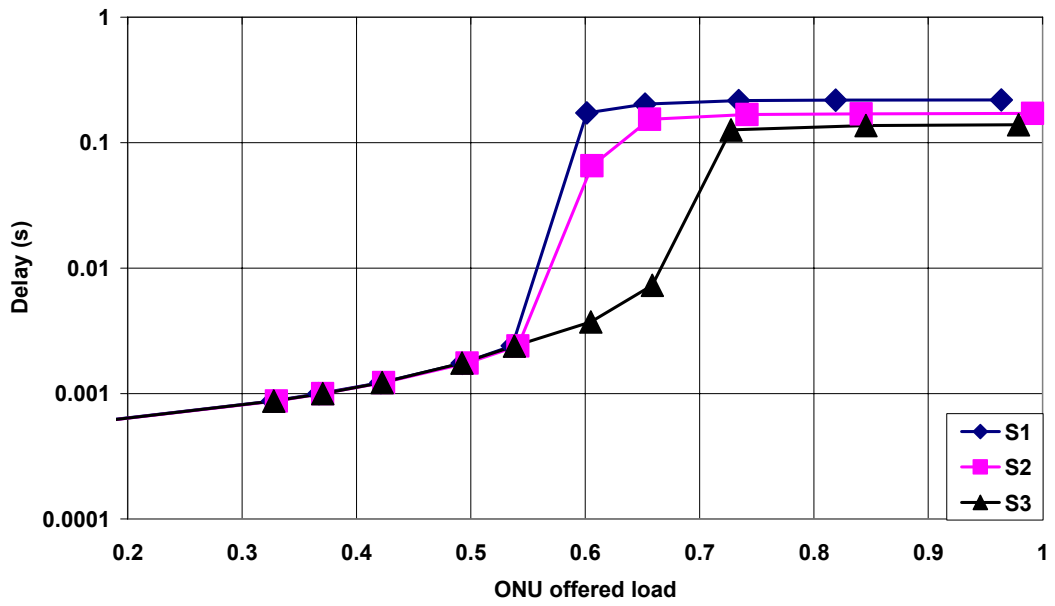


Figure 4-10 Packet delay performance for DMB in GPON when the proportional of ONU in each service level from high to low is set to 7:2:7

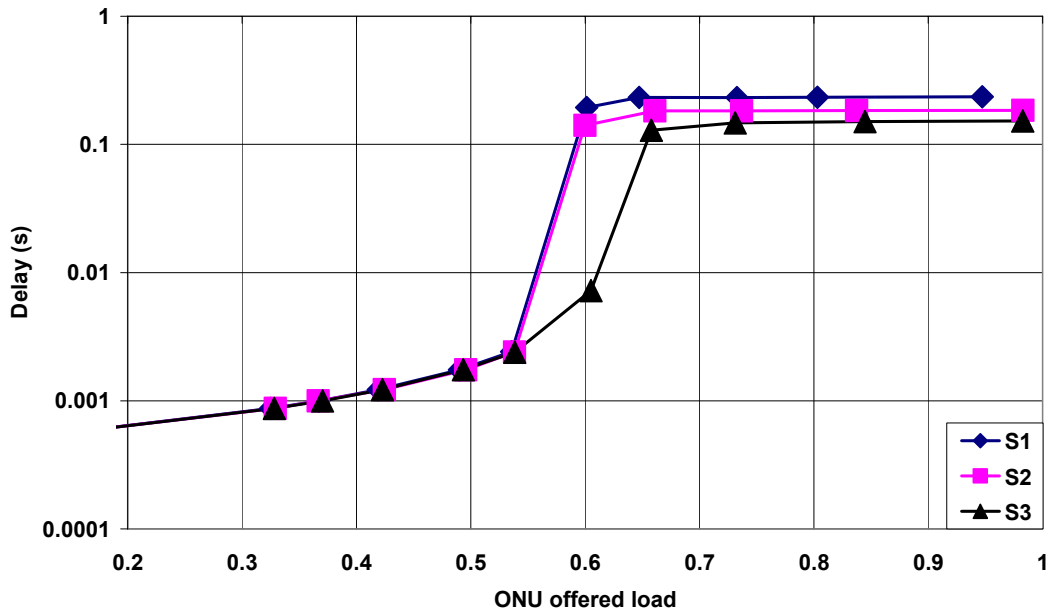


Figure 4-11 Packet delay performance for DMB in GPON when the proportional of ONU in each service level from high to low is set to 10:2:4

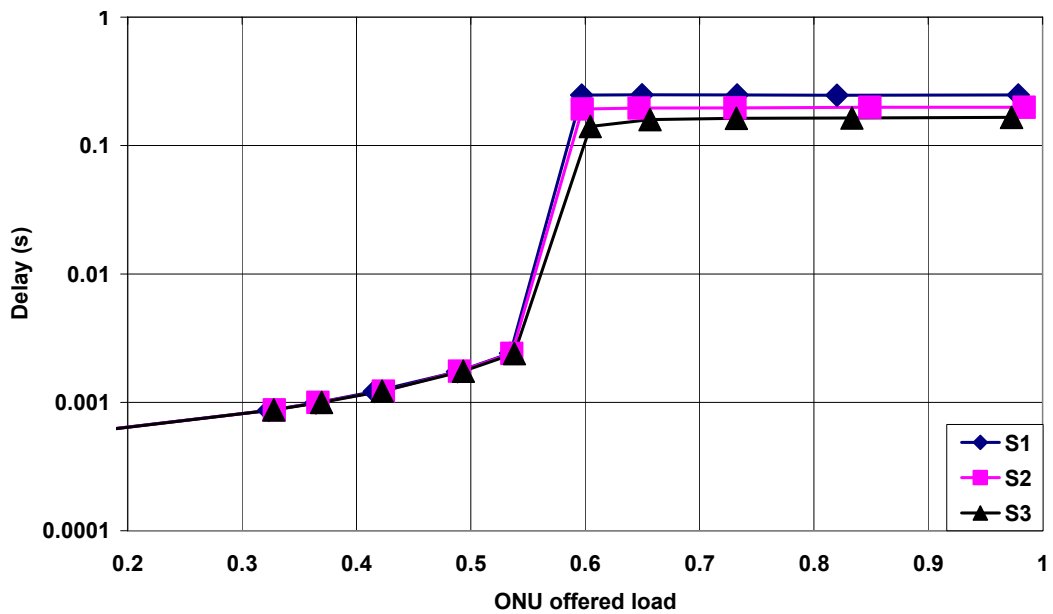


Figure 4-12 Packet delay performance for DMB in GPON when the proportional of ONU in each service level from high to low is set to 14:1:1

Finally, to assess the network performance when only a fraction of subscribers use their assigned guaranteed bandwidth, the number of ONUs in SL_3 , SL_2 and SL_1 is set initially to 2, 6 and 8 respectively, to represent a typical network operation. Subsequently the traffic load of half of these ONUs has been gradually increased from 33 Mbit/s fixed traffic loading to simulate increased bandwidth requirement.

The observed channel throughput responses for the DMB and IPACT algorithms are shown in Figure 4-13. It becomes evident that superior channel throughput was achieved for the DMB algorithm, extending from 853 Mbit/s recorded with IPACT to 901 Mbit/s, demonstrating notable increment in line rates of up to 48 Mbit/s with a commanding bandwidth allocation efficiency of 90%.

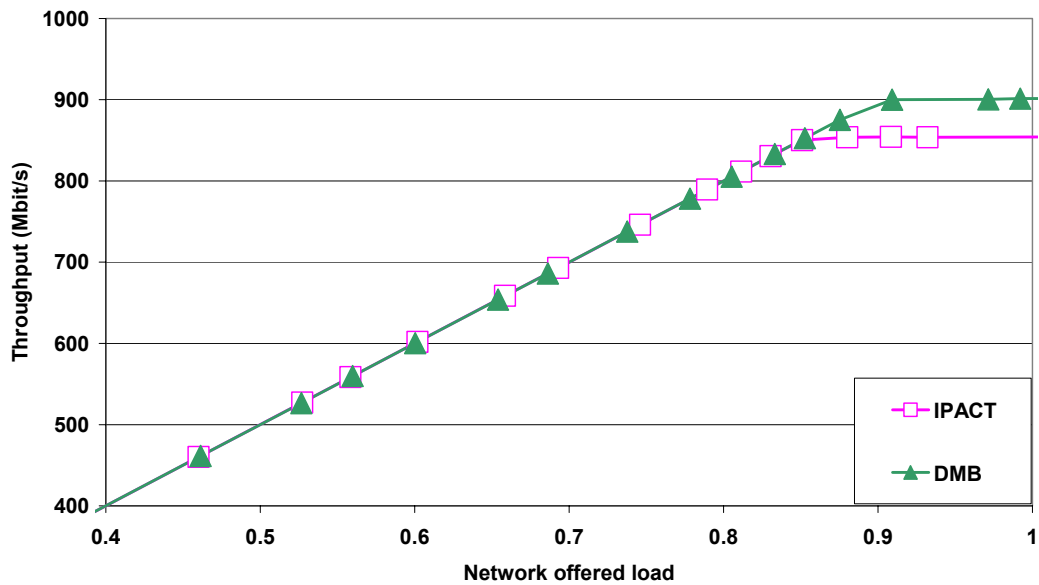


Figure 4-13 Channel throughput for IPACT and DMB in GPON when the proportional of ONU in each service level from high to low is set to 2:6:8

Subsequently, Figure 4-14 exhibits the overall performance attributes by means of attaining the packet delay under regular traffic load for ONUs with different service levels. The established maximum packet delay in DMB is again 10 times less than IPACT, with the maximum network operating range with guaranteed low ONU packet delay greatly increased from 71Mbit/s in IPACT to 75, 77 and 80 Mbit/s for the various service levels respectively, providing more effective transmission of real-time services.

When the ONUs' offered load is greater than 75 Mbit/s and the total user requirement in bandwidth exceeds the overall network capacity, the DMB algorithm still demonstrates the capability to allocate bandwidth with the highest service level ONUs enjoying significantly lower packet delay and loss rates as confirmed by Figure 4-14 and Figure 4-15. In particular, the recorded packet loss rate traces in Figure 4-15 confirm that the maximum throughput achieved by ONUs with no loss, extends to 75, 81 and 90 Mbit/s for service levels 1, 2, and 3 respectively in contrast to 73 Mbit/s in IPACT.

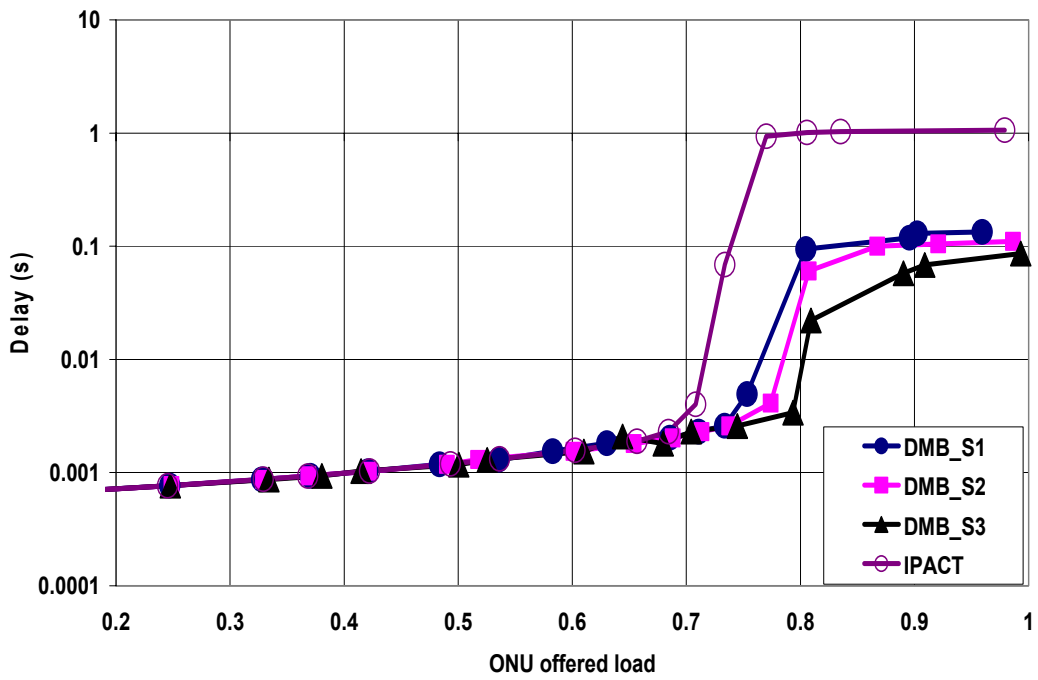


Figure 4-14 Packet delay for three service levels in DMB in GPON when the proportional of ONU in each service level from high to low is set to 2:6:8

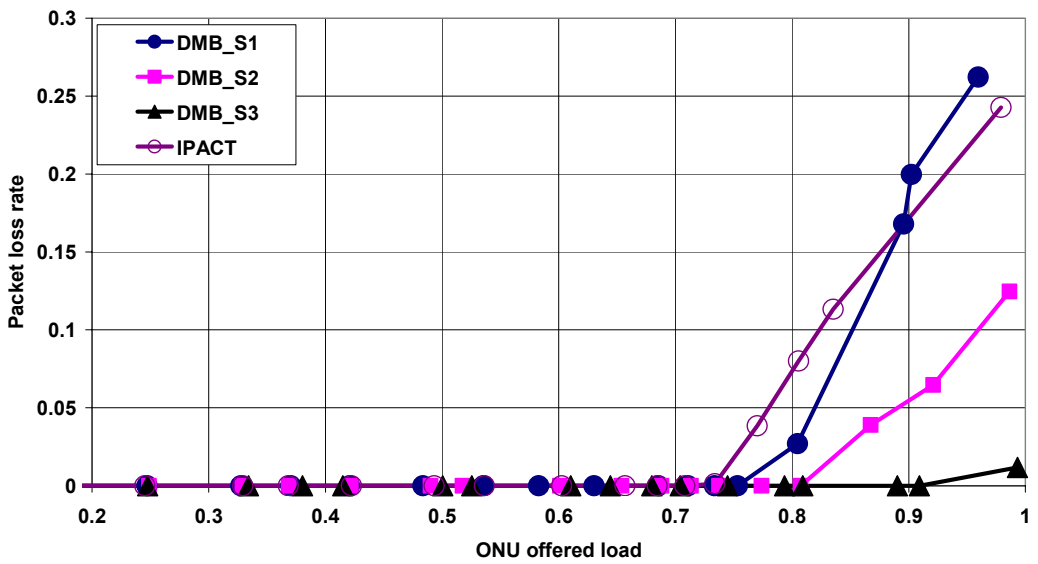


Figure 4-15 Packet loss rate for IPACT and DMB in GPON when the proportional of ONU in each service level from high to low is set to 2:6:8

4.4 Summary

This chapter presented the development of a novel DBA protocol exhibiting impartial and highly efficient bandwidth arrangement for TDM-GPONs. Contrasting with the presented DBA algorithms which only supporting a single service level and working at fixed aggregate data rate, the DMB protocol can flexibly assign ONUs three kind of service levels at different aggregate data rate to meet GPON features and ISP SLA patterns.

To evaluate the performance of the DMB algorithm, the TDM-based scheme is implemented on OPNET Modeller platform. In the simulation, the value of modelled network traffic is based on a self-similar traffic distribution that has an infinite width. Since it is not possible to include the whole width of the distribution, the simulation time is set to be at least long enough to involve, typically, 95% of the distribution area. Additionally, the upstream data can be temporally buffered in each ONU before transmission. To assess an accurate packet delay and packet loss rate, the simulation time is also set to long enough to get a balance between the packet loss rate and transmission rate.

Contrasting the proposed scheme with alternative reported EPON algorithms, simulation results have demonstrated reduced mean packet delay accomplishing up to a tenfold decrease at high network load. This is expected to greatly improve the performed quality in particular of T-CONT 4 and T-CONT 3 services. In addition, the presented network performance in packet delay of high service level users is sustained for increased traffic exhibiting network integrity and QoS according to subscriber service levels. In contrast to the T-CONT 3 and 4 services, the maximum allowable packet delay for T-CONT 2 services in GPON is 5 ms. In the worst simulation scenario case, the measured 0.7 ms packet delay at a typical 33 Mbit/s ONU load region allows for minimal propagation loss and delay of time sensitive applications and also minimal accumulation of transmission time to relief congestion in the backbone network. Furthermore, with the ability to efficiently adjust the assigned guaranteed minimum bandwidth among ONUs, the

DMB algorithm presents an advanced competence in utilising the available bandwidth for a GPON network. As demonstrated in the last simulation scenario, the maximum network operating range with guaranteed low ONU packet delay also increased greatly from 71Mbit/s in IPACT to 75, 77 and 79Mbit/s for SL₁, SL₂ and SL₃ ONUs respectively allowing high effective transmission of real-time services.

Chapter 5

Advanced Dynamic Minimum Bandwidth Allocation Protocol in GPONs

To optimise the 90% channel utilisation rate achieved with the DMB protocol, the GPON polling diagram and packet round trip time are further analysed in this chapter to decrease mean packet delay while increasing channel throughput. This has been achieved by adjusting the ONUs' upstream transmission order and modifying the real-time bandwidth requirements of ONUs'. Following the assessment of the advanced-DMB algorithm over the standard GPON simulation model, their extension is considered to long-reach PONs and WDM-PONs applications.

5.1 Introduction

As analysed in detail in preceding chapters, to avoid the accumulation of waiting time in TDM-PON polling cycles, IPACT [85], has adopted an interleaved polling scheme demonstrating fare bandwidth utilisation rate while triggering the development of significant EPON algorithms, such as the two-layer bandwidth allocation (TLBA) scheme [75] and the dynamic bandwidth allocation with multiple services (DBAM) scheme [84]. Although this overlapping scheme manages to reduce the gaps between ONU upstream transmissions intervals, the upstream transmission bandwidth is not yet fully utilised since idle periods still form between successive polling cycles. A similar characteristic, although of reduced scale, seems to be observed in the application of the DMB algorithm as well since the OLT requires receiving all report messages before it computes and

communicates back to ONUs the next upstream bandwidth map. This process results in the formation of idle time-slots in the upstream transmission channel between the instant the last ONU transmitted its bandwidth request and the moment the first ONU in the successive cycle starts uploading information.

In this chapter, a highly efficient protocol is devised to significantly reduce the transmission frame idle periods and as a result further increase the network throughput while reducing the packet waiting time in ONU buffers. To achieve these characteristics, the ONU transmission order in correlation with their bandwidth request, assignment and launch of packet transfer have been integrated in an advanced DMB (ADMB) algorithm to display diverse GPON throughputs and QoS at various service levels. The performance of the ADMB algorithm will be assessed in comparison with its predecessor at realistic network traffic conditions in terms of channel throughput, mean packet delay, and packet loss rate.

5.2 Development of the Advanced DBA Protocol

The grant and report messages polling order has been extensively considered in the ADMB protocol in an attempt to increase the upstream channel utilisation rate. In addition, since in practical networks the number of upstream packets to be transmitted in a cycle may potentially increase after the report messages have been communicated, the granted upstream time-slots by the OLT will not fully utilise the ONUs' actual bandwidth requirements at the instant of transmission. As a result of these abrupt changes in upstream packets, an up to 2 ms delay could be formed for those later arrived packets, forced to wait in ONU buffers for even up to one polling cycle. In contrast to a 5 ms maximum allowable packet delay specified in the GPON standard for T-CONT 2 services [115], the 2 ms extra delay will cause an accumulation of transmission time to aggravate congestion in the backbone network.

Therefore, in conjunction with the grant and report messages polling order the packet waiting time in ONU buffers has also been explored. To provide a justification of the adopted approach, Figure 5-1(a) displays a TDM bandwidth arrangement polling diagram with a measured 250 μs idle period between successive upstream polling cycles considering a 20 km EPON architecture in the presence of DBA algorithms, such as the DBAM [84] and the TLBA [75]. This idle period is caused by the delay between the last bandwidth-request communication of ONU_n in cycle k and the granting of access to ONU_1 by the OLT in cycle's $k+1$ upstream bandwidth map.

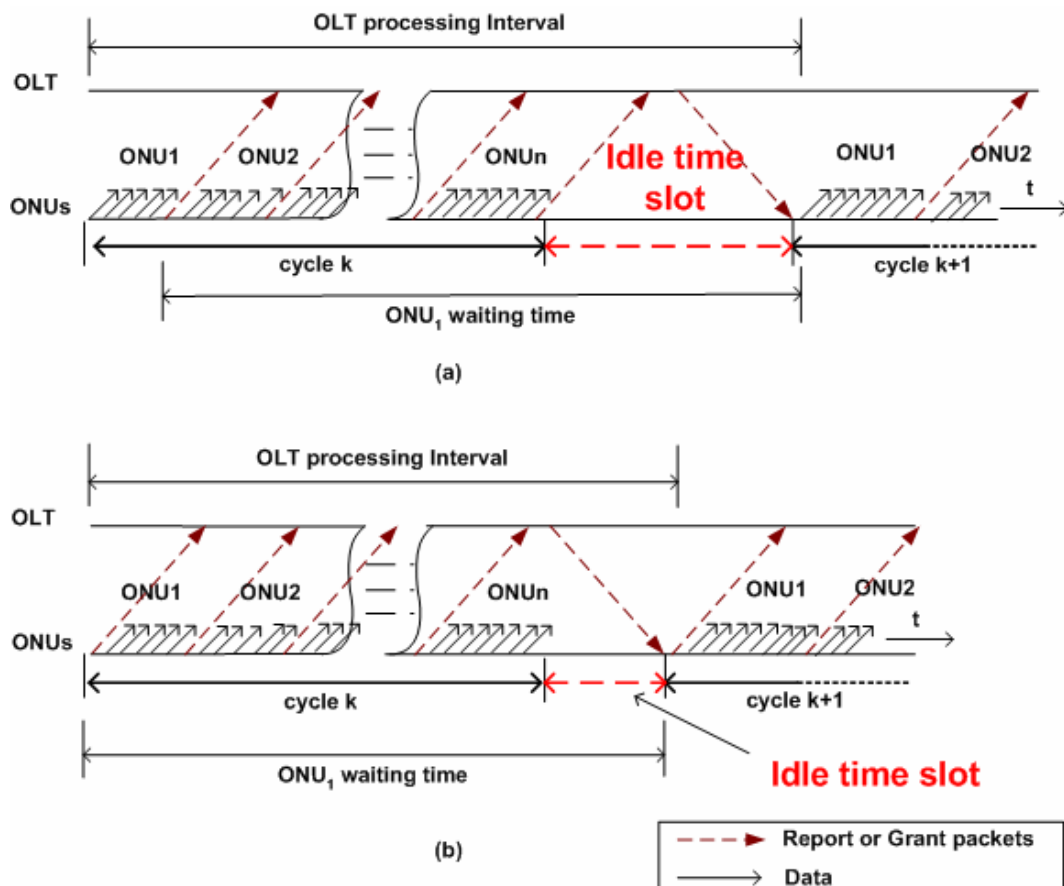


Figure 5-1 Upstream transmission time scales for (a) DBAM and (b) DMB

As opposed to the EPON standard, the ONU report messages in the GPON standard [28], shown in Figure 5-1(b), are transmitted at the beginning of each upstream time-slot, allowing the overlapping in each cycle of part of the idle period with the last ONU upstream transmission interval, providing as a result

greater channel utilisation rate than EPON. To build further on that characteristic, if the last ONU's upstream transmission period is longer than the grant-report messages communication interval between two cycles, then no idle period is expected to be formed in the upstream channel. Consequently by assigning the ONU with the longest upstream transmission period to the last upstream time-slot the overlapping period will be maximised.

In addition, to reduce the packet waiting time in ONUs, the polling mechanism has been explored from another point of view. As shown in Figure 5-2, some upstream data in a cycle may reach an ONU buffer after the report messages have been transmitted to the OLT. Physically the granted upstream time-slots for that ONU will not be representing an accurate bandwidth requirement for that cycle, causing unnecessary data congestion in ONU buffers. Therefore the reported bandwidth requirement should be in the position to be dynamically adjusted to account for these very typical, abrupt changes in data transfer.

According to the network traffic self-similarity, the ONU upstream packet arrival rate in a short period of time is most likely to be constant [84, 104, 141]. If the ADMB protocol can estimate the packet arrival rate and subsequently superimpose a credit value to each ONU original bandwidth requirement, the achieved packet delay performance is expected to be enhanced. Even in the worst case scenario in which the estimated credit bandwidth proves to be totally unnecessary, only a slight increase in TDM delay will have been introduced into the transmission. In particular in comparison with the original polling mechanism where the additional packets would have to wait for a complete polling cycle before being transmitted, the low possibility of slightly increasing the TDM delay would be acceptable.

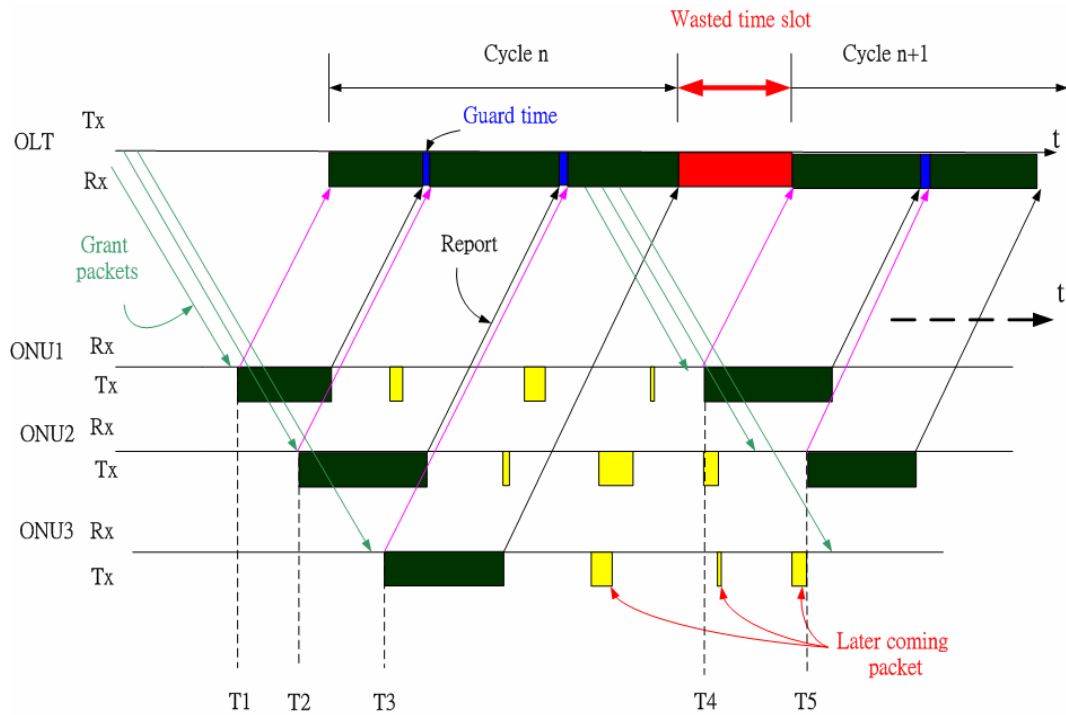


Figure 5-2 TDM-DBA polling diagram in access GPON

5.2.1 The Advanced Bandwidth Allocation Mechanisms

To dynamically assign the allocated bandwidth among ONUs in DMB, the transmission time-slots for each subscriber have been assigned in two stages. In the first stage, the algorithm dynamically assigns each ONU a guaranteed minimum bandwidth, B_{min}^t , from the overall network capacity, to satisfy their basic service requirements at various service levels, t . Furthermore, the OLT apportions any unused bandwidth as an extra assigned bandwidth, $B_{ex_assigned}$, to ONUs according to their buffer queuing status. Therefore, following possible variations in network conditions, the DMB protocol is capable of readjusting the guaranteed minimum and unused bandwidths among ONUs to comply with subscriber contracts. Figure 5-3 (a) repeats the upstream transmission polling cycle diagram of DMB, already shown in Figure 5-3 (b), for direct comparison with that applying to the ADMB algorithm, showing the ONU report messages transmitted at the beginning of each upstream time-slot according to the GPON standard [28]. Due to the burst mode transmission in each ONU, the variation of

the transmission interval period can be extremely different in each polling cycle. With the purpose of maximising the overlapping period in each cycle between the idle periods with the last ONU upstream transmission interval, a comparison mechanism is inserted at the end of the DMB bandwidth assignment function to determine and adjust the longest upstream transmission interval into the last upstream transmission time-slot. As a result, the idle period in each polling cycle, as presented in Figure 5-3 (b), is constantly minimised to increase the channel utilisation rate.

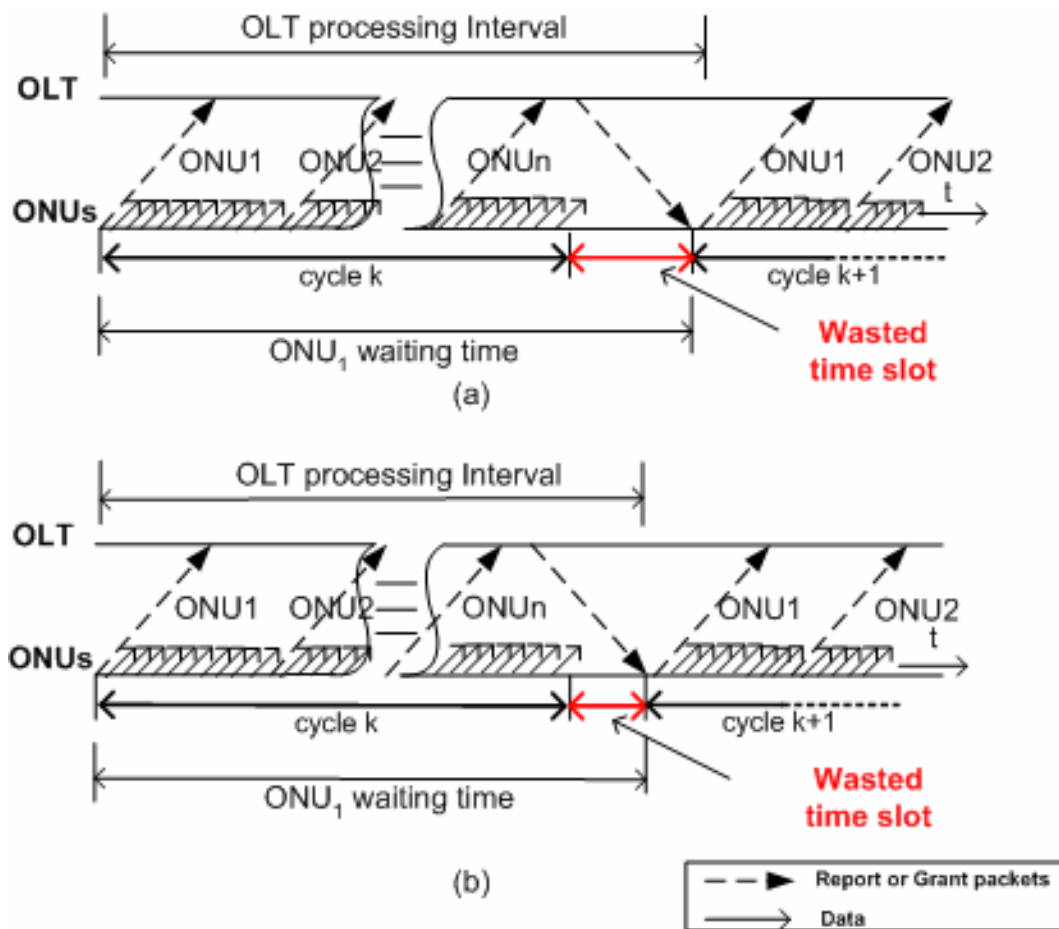


Figure 5-3 Upstream transmission time scales for DMB (a) and ADMB (b)

Alongside the increased network throughput, the developed algorithm as extensively mentioned is also expected to reduce the packet waiting time in the ONU buffers by adding an estimated credit to each bandwidth requirement.

The first step in estimating each ONU credit is to account for its data arrival rate in the upstream buffer, assuming that it will remain constant for two successive cycles [84, 104, 141] to reflect more accurately the variations in ONU bandwidth. This is because that if a data sampling interval is small enough, two successive sampling values will be similar. As a result, this can be achieved by dividing the original bandwidth requirement with the preceding OLT processing interval length. Subsequently, for individual ONUs, the credit values will be calculated by multiplying the data arrival rate with the corresponding waiting time between cycles resulting in the actual bandwidth requirement, R'_i , given by eq. 5-1.

$$R'_i = R_i + \left(\frac{R_i}{proc_interval_length} \times waiting_time \right) \quad (5-1)$$

Then, the allocated bandwidth for ONU_{*i*}, $B^i_{allocated}$, will be determined by using eq. 4-7 but substituting for the new value of R'_i according to eq. 5-2:

$$B^i_{allocated} = \min \left(\begin{array}{l} B^t_{min} + B^i_{ex_assigned} \\ R'_i \end{array} \right) \quad (5-2)$$

5.3 The ADMB Model Implementation and Analysis

The ADMB algorithm, similarly to DMB and IPACT has been used to define the OLT process model of the GPON simulation platform comprising a single OLT and 16 ONUs. For the purpose of simulating a pragmatic network scenario, two ONUs are set to operate at the highest level SL₃, six at a medium level, SL₂ and eight at the lowest service level provisioning, SL₁. Each ONU in the model is assigned to a maximum channel capacity of 100 Mbit/s at fixed 1 Gbit/s aggregate upstream data rate over 25 km link length. In addition, a 2 ms maximum cycle period and 96 bits guard time are considered to establish reliable data transfer between the OLT and ONUs [27, 117].

The first simulation scenario devised at this stage aimed to investigate the network maximum channel throughput performance by reducing the idle periods between successive polling cycles. This was directly achieved by changing the ONU upstream transmission order and assigning an ONU with 10% and 90% of the overall ONU offered load respectively at the last transmission slots. The remaining ONUs were set to experience gradual increase in traffic load under a Pareto self-similar traffic model with a typical Hurst parameter of 0.8 to present practical network traffic.

Subsequently, to confirm the ability of the ADMB algorithm to dynamically assign bandwidth to each ONU under various network traffic conditions, half of the network ONUs in the second simulation scenario have been set to operate at fixed traffic load, representing 33% of the assigned ONU channel capacity. This is considered adequate for the provision of a HDTV channel at approximately 20M, fast internet at 10M, video conferencing at around 2M and telemetric/remote control at 1M. The remaining half ONUs have undergone a gradually increase in traffic. The recorded algorithm performance was then directly compared and contrasted to the IPACT and DMB algorithms.

5.3.1 Simulations and Performance Analysis

Figure 5-4 exhibits the recorded network throughput for the two conditions of the last ONU traffic load. Simulation results have confirmed the efficiency of the algorithm in increasing the overall throughput from 876 Mbit/s, achieved with low traffic ONUs at 10% in the last transmission slots, up to around 940 Mbit/s when the last ONU has been carrying heavy traffic load, represented by 90% of the overall. Apart from the 6.4% improvement in channel utilisation rate compared to alternative algorithms, the measured 94% channel capacity figure provides a considerable advancement in GPON bandwidth allocation performance.

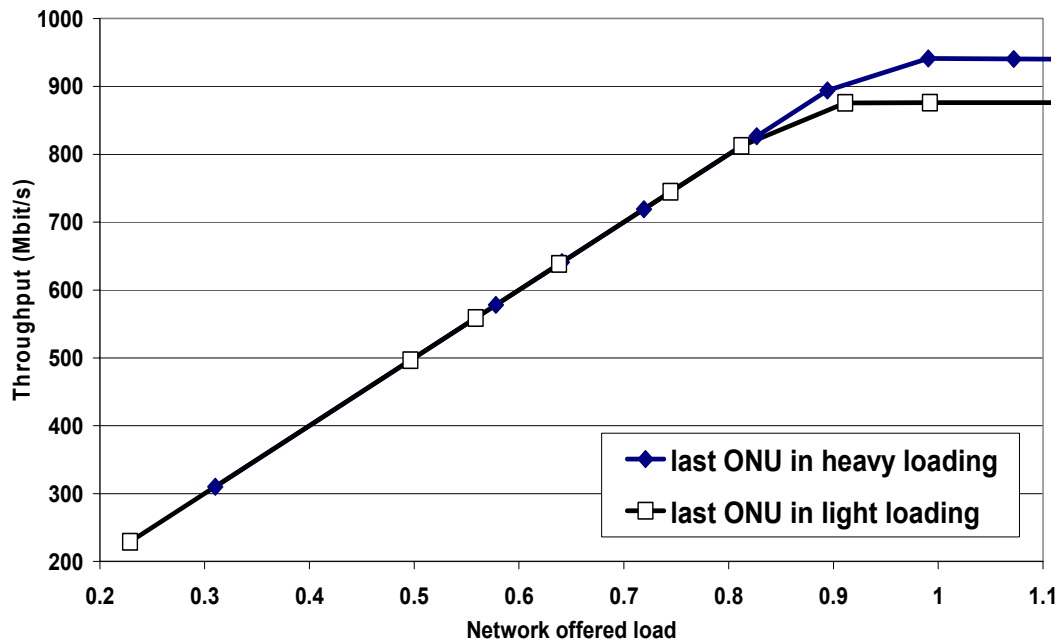


Figure 5-4 DMB Channel throughput performance under two kinds of last ONU loading in GPON

To contrast between the bandwidth allocation efficiency of various algorithms, half of the ONUs are set to operate under fixed 33 Mbit/s traffic load, as mentioned before, to simulate practical network conditions. The observed channel throughput responses for IPACT, DMB and ADMB are shown in Figure 5-5, confirming the superiority of ADMB in terms of channel utilisation rate. The maximum channel throughput accomplished due to the additional characteristics of the algorithm extends from 853 Mbit/s and 901 Mbit/s, achieved with IPACT and DMB respectively, to around 947 Mbit/s demonstrating an up to 100 Mbit/s increase in available line rates, with a commanding bandwidth allocation efficiency of 95%. Such a figure could accommodate additional five HDTV channels or fifty video conference channels to enhance real-time service provision.

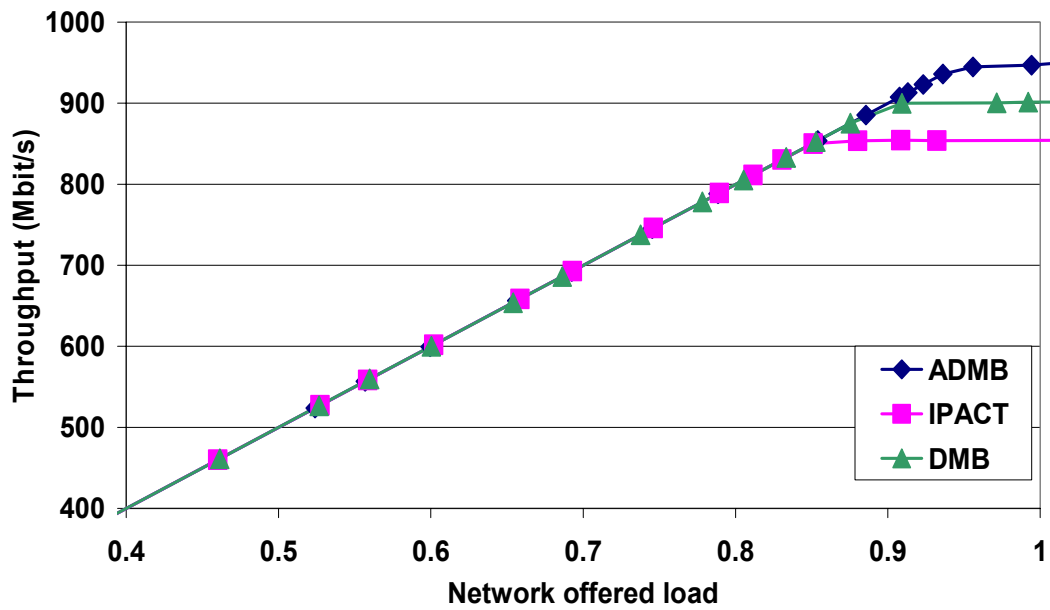


Figure 5-5 Channel throughput for IPACT, DMB and ADMB in GPON

The simulated packet delay responses for fixed-load ONUs are shown in Figure 5-6. It could be concluded that although all algorithms exhibit relatively low delay values (< 3.3 ms), in contrast to a 5 ms maximum allowable packet delay specified in the GPON standard for T-CONT 2 services [115], the application of the ADMB protocol displays the lowest delay with approximately 1.2 times superior performance at low offered load regions, and 1.2 and 1.5 times at high offered load with respect to IPACT and DMB respectively. As a result the measured 0.7 ms packet delay at a typical 33 Mbit/s low ONU load region, allows for minimal loss and delay propagation of time sensitive applications and the accumulation of transmission time to relief congestion in the backbone network.

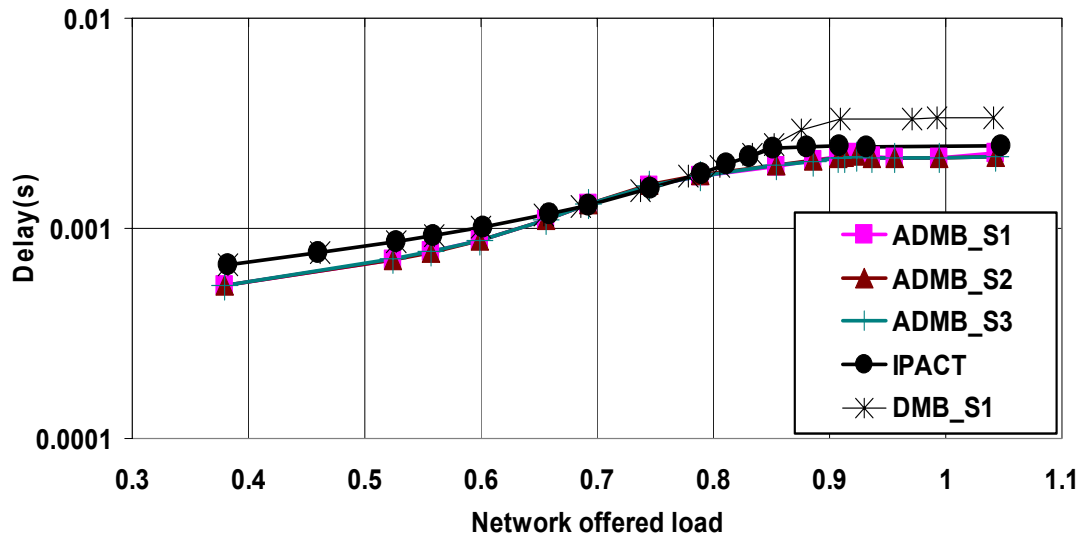


Figure 5-6 Mean packet delay for fixed traffic loading ONUs in IPACT, DMB service level 1 (S1) and ADMB service levels 1-3

Consequently, Figure 5-7 exhibits the overall performance attributes of the IPACT, DMB and ADMB protocols by means of attaining packet delay under regular traffic load for ONUs with different service levels. It is apparent that the ADMB protocol exhibits remarkable delay reduction at high network load by a factor of 10 in relation to IPACT which is expected to greatly improve the performed quality in particular for T-CONT 4 and T-CONT 3 services. In addition, the maximum network operating range with guaranteed low ONU packet delay has also been increased from 71Mbit/s in IPACT and 75, 77 and 79 Mbit/s in DMB to 82.5, 83 and 84 Mbit/s for ADMB service levels 1 to 3 respectively, allowing for more effective transmission of real-time services.

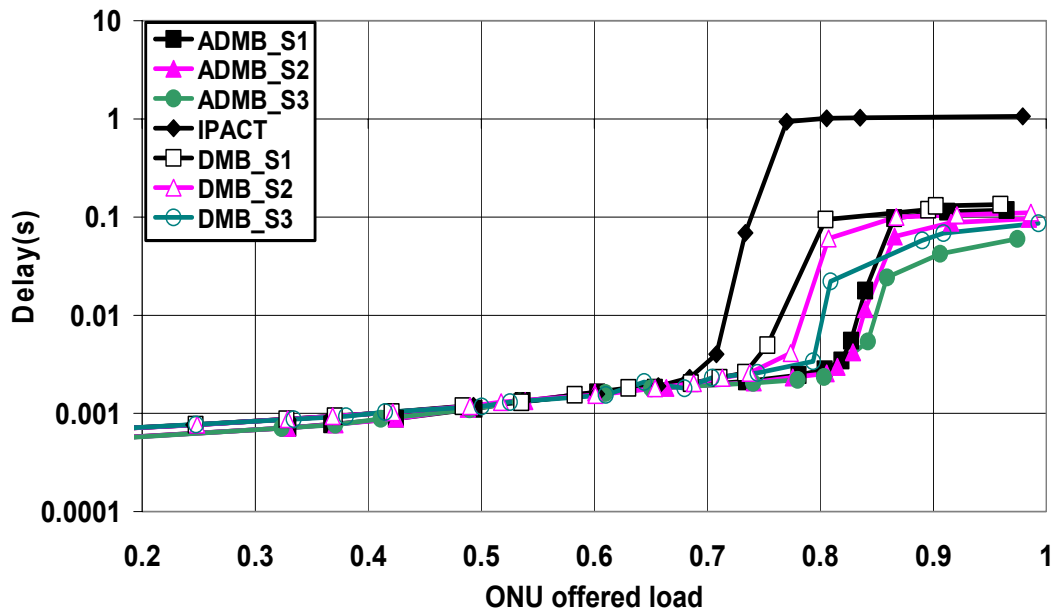


Figure 5-7 Mean packet delay for normal traffic loading ONUs in IPACT, DMB and ADMB

In addition, when the ONUs' offered load is greater than 82.5 Mbit/s, and the total user requirement in bandwidth exceeds the overall network capacity, the ADMB algorithm still demonstrates the capability to allocate bandwidth to the highest service level ONUs enjoying significantly lower packet delay and loss rates as confirmed by Figure 5-7 and Figure 5-8. In particular, the recorded packet loss rate traces in Figure 5-8 verify the maximum throughput achieved by ONUs with no loss, extending to 83, 90 and 100 Mbit/s for service levels 1, 2, and 3 respectively in contrast to 73.6 Mbit/s achieved with IPACT and 75, 80 and 90 Mbit/s with DMB, confirming in all evaluation measures the ADMB enhanced capability to handle real time transmission of services simultaneously for multiple ONUs at increased transmission rates.

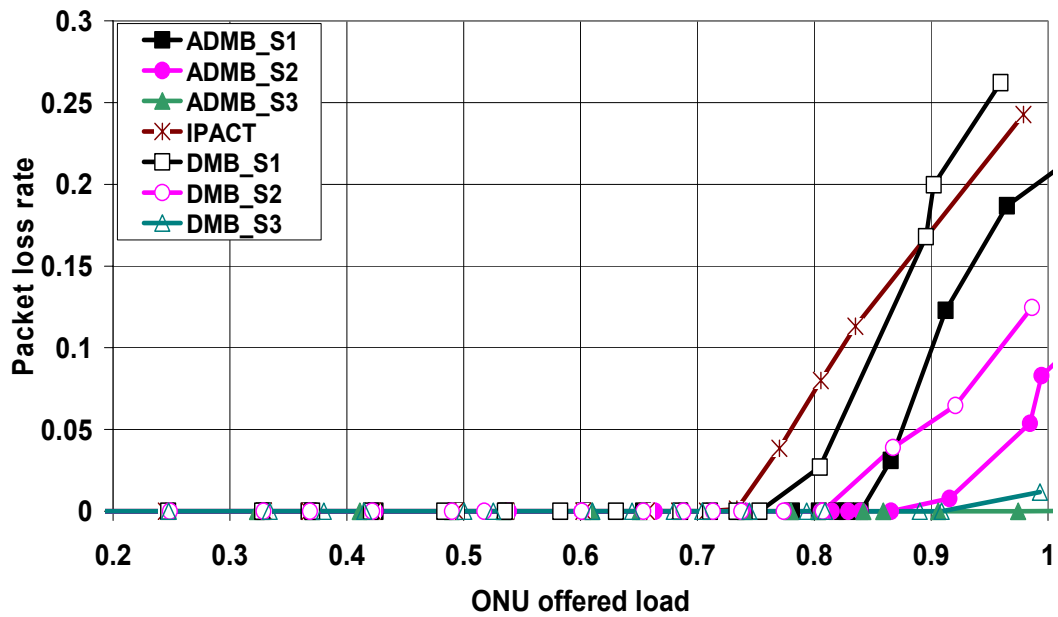


Figure 5-8 Packet loss rate in IPACT, DMB and ADMB

5.4 Summary

This chapter presented the development of an ADMB protocol to exhibit dynamic and highly capable bandwidth assignment in GPONs. In particular, the upstream transmission order of ONUs in each polling cycle is dynamically adjusted according to their time-slot occupancy with the longest transmission period ONU assigned to the last upstream time-slot to reduce idle intervals between bandwidth request, assignment and launch of packet transfer. In addition, each ONU bandwidth requirement is vigorously adjusted based on successive cycle estimations of their buffer upstream data arrival rate to account for real-time modifications during their bandwidth request-assigning process to further reduce the ONU packet waiting time. Contrasting the ADMB scheme with published DBA algorithms, simulation results have shown a notable bandwidth efficiency reaching almost 95% with a significant reduction in mean packet delay and packet loss rate to allow for effective provisioning of high-bandwidth, time-sensitive multimedia services.

Recently, the development of larger-split, longer reach PON architectures has attracted a lot of attentions to simplify the network infrastructure by terminating end users directly to the edge routers of the core network, offering guaranteed QoS with reduced communication delay. To contribute to this research area, the modification of the ADMB algorithm will be considered in the next chapter to demonstrate data transmission with comparable performance measures for much longer network spans compared to standard PON provision.

Chapter 6

Dynamic Bandwidth Allocation Protocol in Long-reach GPONs

To extend the connection distance in standard GPON over 100 km integrated access/metro link lengths, a novel, two-state bandwidth assignment MAC protocol is presented demonstrating network resilience and highly-efficient bandwidth allocation for long-reach gigabit passive optical networks. The protocol enables the optical line terminal to overlap the idle time-slots in each packet transmission cycle with a virtual polling cycle to increase the effective transmission bandwidth. Contrasting the new scheme with a developed algorithm, network modelling has exhibited significant improvement in channel throughput, mean packet delay and packet loss rate in the presence of class of service and service level differentiation.

6.1 Introduction

Comparing with the current broadband network systems, such as DSL and WiFi, GPONs can provide already in their standard implementations much higher bandwidth with longer connection distance ranging in theory up to 60 km [26]. For the purpose of further increasing the connection distance to reduce number of COs, there has been growing interests in the development of a larger-split, longer-reach PON to reduce the cost of high bandwidth connections over 100 km integrated access/metro link lengths [76]. By reducing the number of COs, the CAPEX as well as the OPEX is reduced. In addition, by directly communicating

the network traffic from subscribers' premises to an edge switch in a long-haul network, the QoS for various multimedia services such as HDTV and VoD can be further enhanced, since service provider and ISPs could directly apply centralised management of ONU requirements [128, 131]. However, the basic long-reach scheme, using TDM scheme to share the bandwidth, has been limited to architectures which can only be shared by approximately 16 to 32 subscribers. In order to extend the number of subscribers, there is a trend to hybrid WDM with TDM together to further increase the bandwidth and share the cost [76, 98, 126, 132]. Those hybrid architectures are formed by adding a wavelength router before the optical splitter and work as multiple virtual TDM PONs. In the architecture, each virtual TDM-PON is assigned with one or two specific wavelengths for both downstream and upstream transmissions that are similar with the basic TDM-PON topology. The downstream signals for various PONs are modulated with different dedicated wavelengths light sources and then combined together before sending out. Since the downstream signals are modulated by diverse wavelengths light sources, they can be transmitted in a single fibre and then routed into each dedicated optical splitter for each virtual TDM-PON. Each of the downstream signals is then split to N copies for N ONUs. Similarly, the reversed path will be adapted for the upstream transmissions.

In those hybrid schemes, the architecture is spread to multiple virtual TDM-PONs, so the number of supportable subscribers is greatly increased. Since the long-reach PON architecture is formed by multiple virtual TDM-PONs and each one works independently, as a result, each virtual TDM-PON can be driven by an independent TDM-DBA algorithm. However, by reason of long propagation delay, the direct implementation of access TDM-DBA protocols will present a low channel utilisation rate and high packet delay. To overcome the issue, the focus of the work presented in this chapter is to implement a novel DBA protocol for long-reach GPON architectures with the aim of utilising every idle time-slots to increase the available transmission bandwidth in the presence of CoS and service level differentiation. In this case, the internet service providers can easily add/off

different classes of multiple services with suitable QoS and can demonstrate network integrity according to subscriber service levels.

6.2 Development of a DBA Protocol for Long-reach GPONs

As discussed in Chapter 5, to achieve service level integration, according to the GPON standard [26], the OLT has to receive all of the bandwidth requirements from ONUs before it imparts the upstream bandwidth maps to notify ONUs about their allocated windows. As a result, the upstream network channel will remain idle between two polling cycles. In view of a 100 km typical long-reach PON [26], direct implementation of the DMB or other DBA protocols are expected to display limited bandwidth utilisation since additional time-slots remain idle in each polling cycle in comparison to standard GPONs. This is due to an up to 500 μs increase in packet propagation time from 125 μs in 25km-PONs. As illustrated in Figure 6-1, a total 1000 μs will remain idle in each cycle due to the communication of bandwidth requirements and the upstream bandwidth maps among OLT and ONUs. To achieve compelling channel throughput and packet delay performances, a novel two-state DMB (TSD) protocol is developed to eliminate the idle periods. Accordingly, the idle time-slots will constitute virtual polling cycles where the ONUs can transmit data by means of a prediction method to estimate their bandwidth requirements [84, 104].

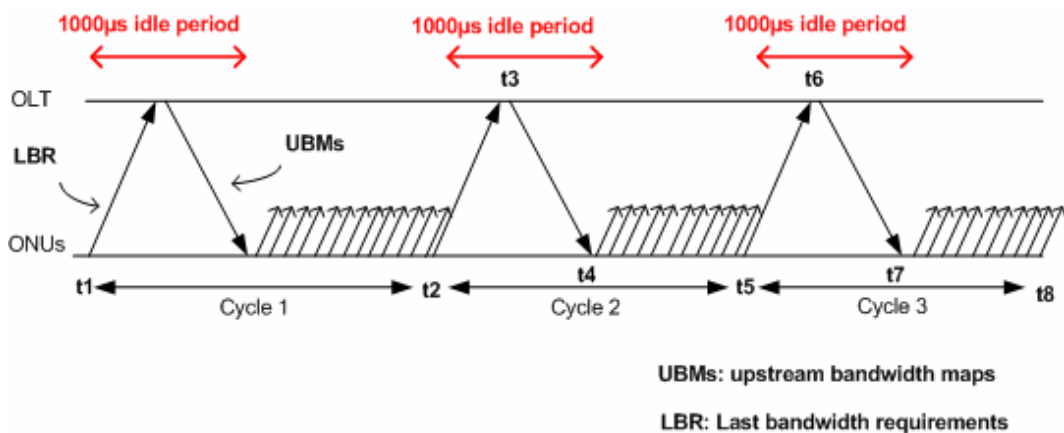


Figure 6-1 DMB transmission mechanism in long-reach GPON

In a TDM-MAC protocol, since ONUs can only transmit their data at the assigned time-slots, the OLT in the TSD protocol needs not only to arrange the regular upstream bandwidth maps for ONUs according to their report messages but also to arrange the virtual upstream bandwidth maps according to ONU estimated bandwidth requirements. Similar to the ADMB protocol, the first step in estimating ONU bandwidth requirements is to account for their upstream buffer data arrival rate, assuming that it is highly possible to remain constant for two successive cycles, as already explained in Chapter 5, to reflect variations in ONU bandwidth accurately [84, 104, 141]. The data arrival rate then can be obtained by dividing the original bandwidth requirement with the preceding OLT processing interval length. Subsequently, the OLT can calculate the estimated bandwidth requirement for each ONU by multiplying its data arrival rate with the relative waiting time period and then the OLT can assign and transmit the grant messages before the start of each virtual cycle.

6.2.1 The Long-reach PON Bandwidth Allocation Mechanisms

As shown in Figure 6-2(b), the upstream bandwidth maps in cycle 2, for example, will be imparted downstream at time instant t_3 , subsequent to the reception by the OLT of all ONU bandwidth requirements, for this polling cycle, R_i^g , where i and g denote the ONU number and time instant indicator respectively. As a result, the effective time-slots engaged for data transmission in cycle 2 are limited between t_4 and t_5 . To take advantage of the succeeding idle period t_5 to t_7 in cycle 3, the protocol embarks the practical transmission period in cycle 2 to communicate virtual grant packets scheduled to reach ONUs before t_5 , denoting the beginning of polling cycle 3. Therefore, ONUs can effectively utilise the idle periods, t_5 to t_7 for significant data transfer.

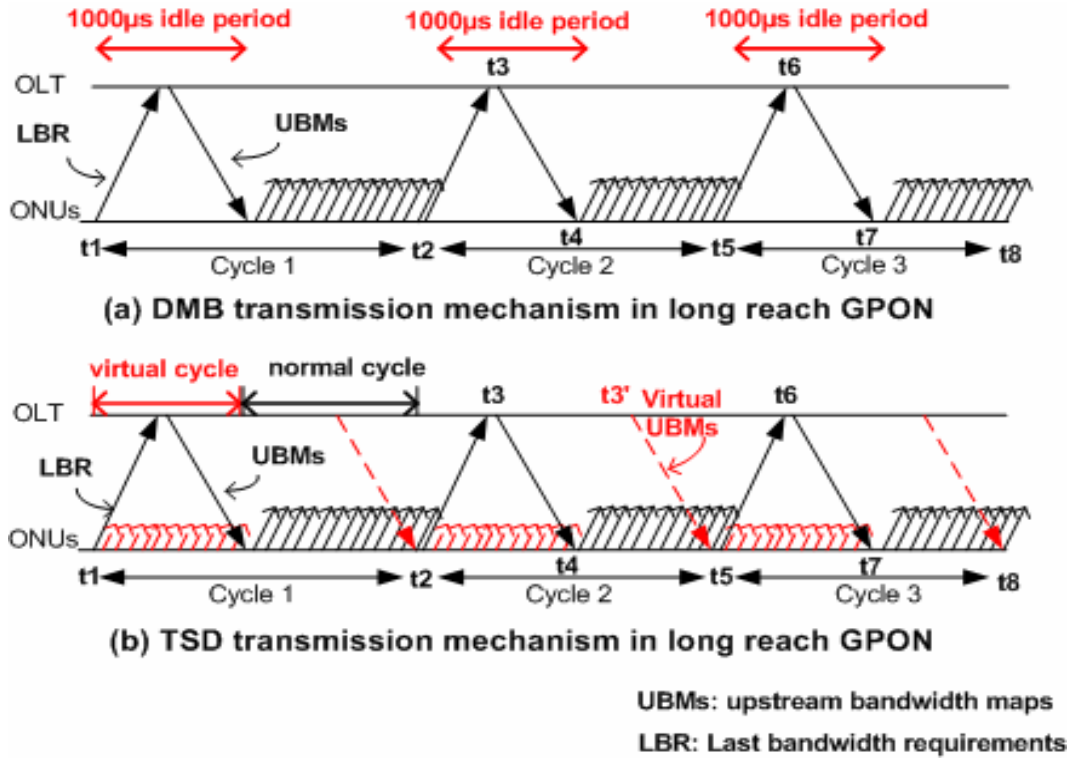


Figure 6-2 TSD transmission mechanism in long-reach GPON

The amount of virtual bandwidth, BW_i , allocated to ONU_i will be determined by the DMB algorithm [117], with each $1000 \mu s$ idle period regarded as the maximum polling period parameter, in terms of an estimated bandwidth requirement. According to the traffic self-similarity [84], since the data arrival rate can be similar in a short period of time, the estimated required bandwidth, $R_i^{3'}$ for ONU_i during the cycle 2 period t_2 to t_5 , will be directly proportional to its actual bandwidth requirement R_i^3 in cycle 1 period from t_1 to t_2 , as shown in eq. 6-1.

$$R_i^{3'} = \left(\frac{t_5 - t_2}{t_2 - t_1} \right) R_i^3 \quad (6-1)$$

To determine the actual requirement in bandwidth of ONU_i for subsequent cycles, the virtual bandwidth BW_i for each cycle should be subtracted to take into account the packet transfer taken place during the corresponding virtual bandwidth period.

6.3 The TSD Model Implementation and Analysis

To evaluate the proposed algorithm in terms of channel throughput, packet delay and packet loss rate, a 100 km-span, 16-split model is developed in OPNET Modeller envisaging three service levels, SL_t , $t = 1, 2, 3$, from low to high to comply with typical service provisioning [117]. The number of ONUs in each service level is set to 8, 6 and 2 for service levels low to high respectively. Similar with the GPON simulation model, each ONU is dispensed a maximum information rate of 100 Mbit/s, at a total 1 Gbit/s aggregate capacity, assigning a 2 ms maximum cycle period and 96 bits guard time to establish packet transfer between the OLT and ONUs. The network traffic is also implemented by a Pareto self-similar traffic model with a typical Hurst parameter of 0.8 to simulate practical network patterns.

In the absence, to the best of our knowledge, of published long-reach GPON MAC protocols, the proposed algorithm performance is best evaluated by contrasting it to the DMB algorithm, having outperformed competitive GPON protocols [117], applied to the current long-reach model.

The guaranteed minimum bandwidth, B_{min}^t , in the DMB and TSD algorithms is dynamically assigned to satisfy the basic service requirements, corresponding to the T-CONT 2 and part of T-CONT 3 traffic. Since the value of B_{min}^t in each polling cycle is calculated dynamically according to the overall network capacity and ONUs' service levels, system providers could straightforwardly add and remove services to a subscriber access without influencing other network users. Furthermore, not all subscribers will end up using their dispensed B_{min}^t bandwidth at each cycle, and as a result the unused bandwidth can be allocated as an extra assigned bandwidth, $B_{ex_assigned}$, to support T-CONT 4 traffic.

Also when ONUs receive their upstream bandwidth maps, the strict priority queue method could allow sequential delivery of T-CONT2, T-CONT3 and finally T-CONT 4 traffic. As a result all traffic types are expected to enjoy a smooth

transmission under low network loading while specific to experience penalties when the overall traffic loading exceeds the maximum network capacity. According to traffic performance tolerance ranges, a longer packet delay and packet loss rate are expected for T-CONT 4 at high network load, allowing for bandwidth to be allocated effectively to support the other two traffic classes. Similarly, T-CONT 3 traffic will start suffering longer packet delay and packet loss rate for further increased loading. In that sense, the necessary QoS per service can be effectively ensured by the TSD protocol.

6.3.1 Simulations and Performance Analysis

Figure 6-3 confirms superior performance of the TSD protocol in terms of achieved network throughput, allowing for network load values to increase up to around 987 Mbit/s, compared to the DMB that stalls at only 680 Mbit/s. As a result, apart from the 45% improvement in channel utilisation rate, the measured 98.7% maximum channel capacity figure displays network utilisation comparable to the application of the DMB protocol in standard GPONs [117].

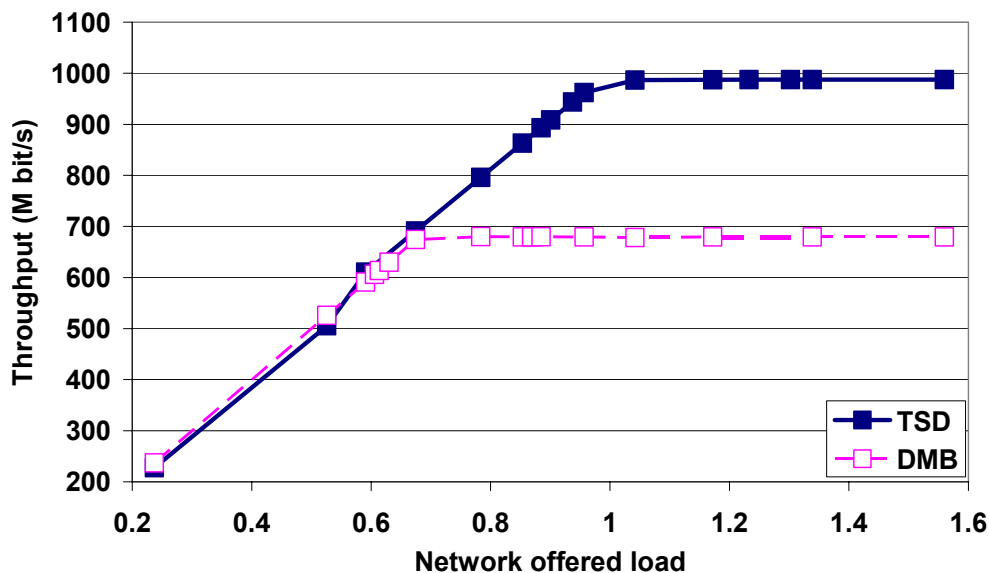


Figure 6-3 Channel throughput for TSD and DMB in long-reach GPON

To examine the data transfer performance, Figure 6-4 exhibits the mean packet delay for all three SLs versus ONU offered load for each algorithm. The TSD

algorithm demonstrates significantly lower mean packet delay figures than DMB, exhibiting almost 30 and 25 times reduction at around 55% ONU loading for SL₁ and SL₂ respectively and approximately 8 times reduction at an extended 70% loading for SL₃. It also becomes evident from this figure that the ONU traffic load, before packet delay reaches the 5 ms limitation for time sensitive traffic, have been extended from 39, 42 and 53 Mbit/s to 59, 65 and 78 Mbit/s for SLs 1, 2, and 3 respectively. The gained 20, 23 and 25 Mbit/s bandwidth for SLs 1, 2, and 3 ONUs can then be utilised to support addition multimedia services for each ONU, such as online game, education-on-demand and video conferencing [16].

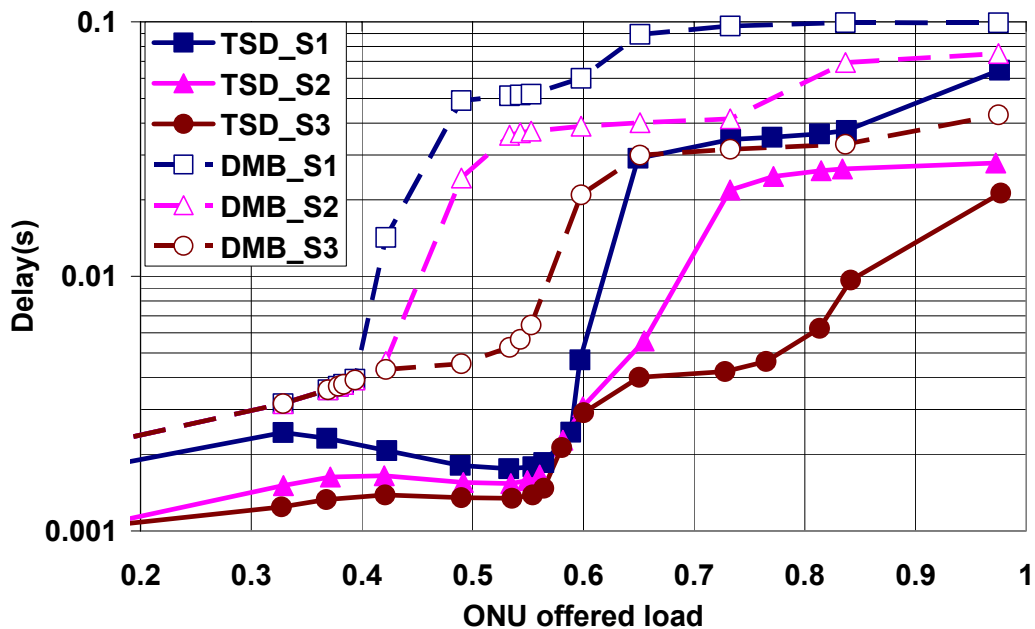


Figure 6-4 Mean packet delay for TSD and DMB in long-reach GPON

Furthermore, as shown in Figure 6-5, the proposed scheme also provides considerable improvement in terms of packet loss rate. Comparing the responses of the two protocols for the worst case scenario SL₁, loss-free transmission is extended from network load 674 Mbit/s ($1000 \text{ Mbit/s} \times 0.674$) to 956 Mbit/s ($1000 \text{ Mbit/s} \times 0.956$) providing an extra 282 Mbit/s network capacity for ISPs either to provide more real-time services to subscribers or support higher number of subscribers.

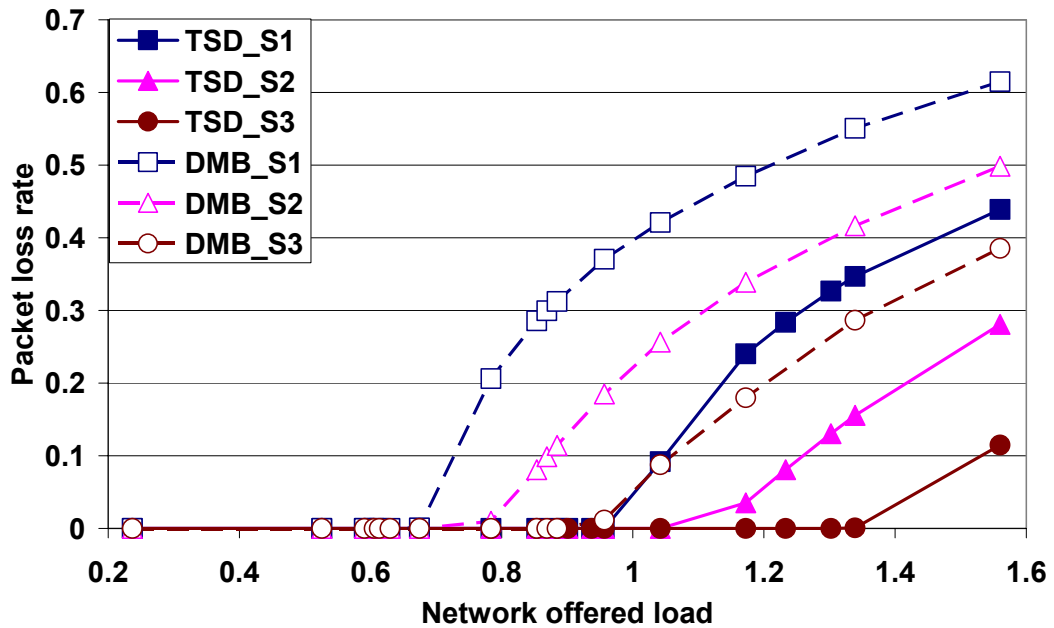


Figure 6-5 Packet loss rate for TSD and DMB in long-reach GPON

To consider the CoS differentiation in the long-reach network and to simulate a realistic network model, the population of each traffic in the simulation is set to 20%, 40% and 40% for T-CONT 2, 3 and 4 respectively [76, 142]. To that extend the simulation results following illustrate packet delay achieved for each service levels in consideration of the three types of CoS. Figure 6-6 for example exhibits T-CONT 2 traffic performance for all three SLs versus ONU offered load, using the TSD and DMB algorithms.

In contract to a 5 ms maximum allowable packet delay specified in the GPON for T-CONT 2 traffic [115], the 0.76 ms peak delay value in the TSD algorithm exhibits the capability of the scheme to resourcefully transmit T-CONT 2 traffic as apposed to the DMB algorithm. In addition, a threefold reduction is presented at 50% ONU offered load region demonstrating the ability of the TSD protocol to relief transmission congestion in the backbone network.

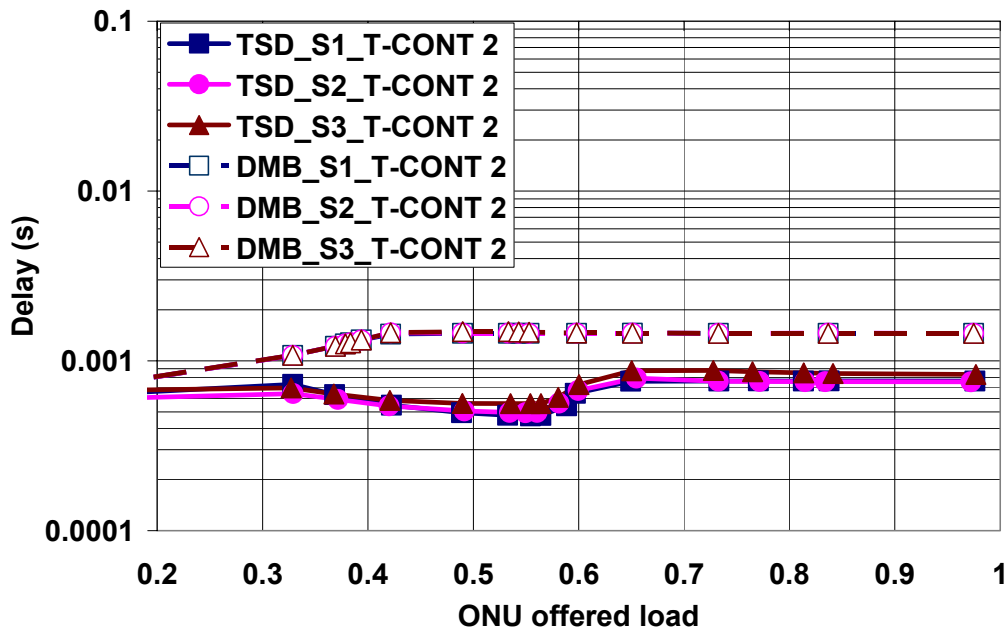


Figure 6-6 Mean packet delay for T_CONT 2 services under 3 kinds of ONU service levels in TSD and DMB

Similar to the profile for T-CONT 2 traffic, T-CONT 3 traffic ONUs exhibit very low packet delay for all three service levels in view of the TSD algorithm shown in Figure 6-7. A strong evidence of almost 70 times reduction in delay is demonstrated for the least priority service level, SL₁ between the ONU loading 65 and 77 Mbit/s regions, and a 50 and 15 times reductions in delay are also presented for SL₂ and SL₃ ONUs respectively at around 90% ONU loading.

It is also clear from this figure that the values of the mean packet delay in DMB are dramatically increased at the ONU offered load 55, 73 and 83 Mbit/s for SL 1, 2 and 3 ONUs respectively, widely extended to 77, 100 and 100 Mbit/s respectively in the application of TSD before the packet delays reach their peaks. Derived from these transfer characteristics, an approximate 20 Mbit/s increase in capacity for each ONU independently of service level would be sufficient to accommodate the extra bandwidth required for error free T-CONT 3 service transmission. Additionally, in contrast to a 100 ms maximum allowable packet delay specified in the GPON standard for T-CONT 3 traffic [115], a 47 ms peak delay value has been recorded in view of the TSD algorithm to release the

transmission time pressure in backbone network. The maximum ONU throughput to provide acceptable delay for T-CONT 3 traffic is then significantly improved from 90, 100 and 100 Mbit/s in DMB to 100 Mbit/s in TSD for all service levels.

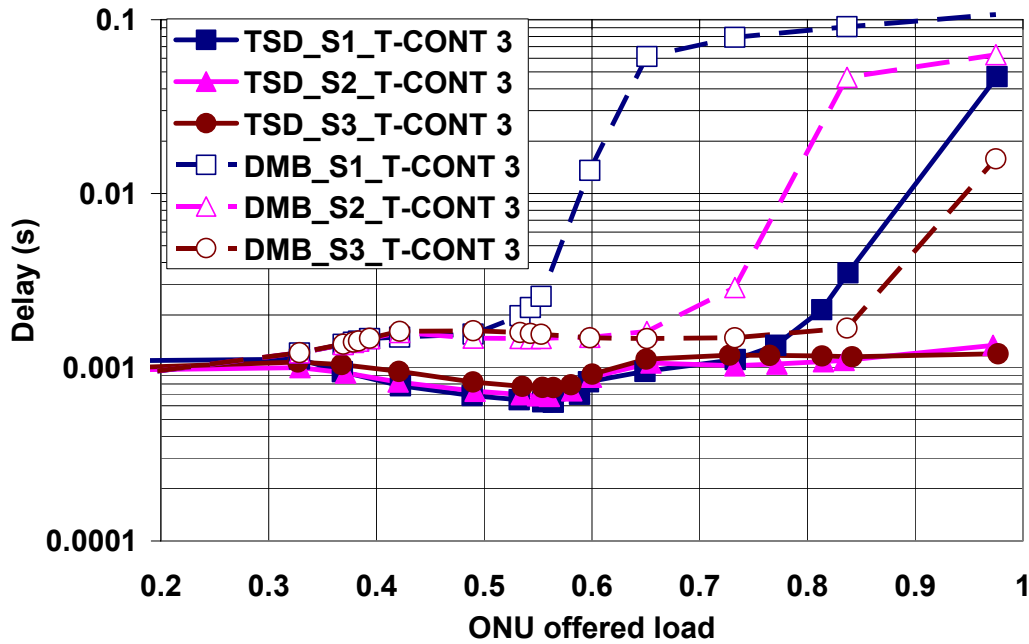


Figure 6-7 Mean packet delay for T-CONT 3 services under 3 kinds of ONU service levels in TSD and DMB

Comparing with T-CONT 2 and 3 traffic, the time insensitive service T-CONT 4, has the lowest priority in accessing the network and as a result expected to present the worst performance in packet delay. This is confirmed in Figure 6-8, with a significantly increased delay figures among the three service levels. In any case though the displayed delay in view of the TSD algorithm is still significantly less than that observed with any other algorithmic.

Considering the traffic responses for SL₁ ONUs, TSD presents roughly 10 times reduction in packet delay for ONU loads ranging between 42 and 83 Mbit/s. Similarly, around 6 to 12 times decreased figures are observed for SL₂ and SL₃ ONUs between 50 to 100 Mbit/s. In addition, the maximum ONU throughput in Figure 6-8 to provide less than the 500 ms [115] maximum acceptable delay for T-CONT 4 traffic, is also extend from 55, 73 and 90 Mbit/s in DMB to 83 Mbit/s

for SL1 and 100 Mbit/s for SL2 and SL3 in TSD. The reduced delay values for each SL ONU are very critical in network operation since they represent in turn reduction in ONU buffer packet waiting time allowing the feeder section in the PON to accommodate increased volume of burst streams depending on network penetration and service level distribution among ONUs.

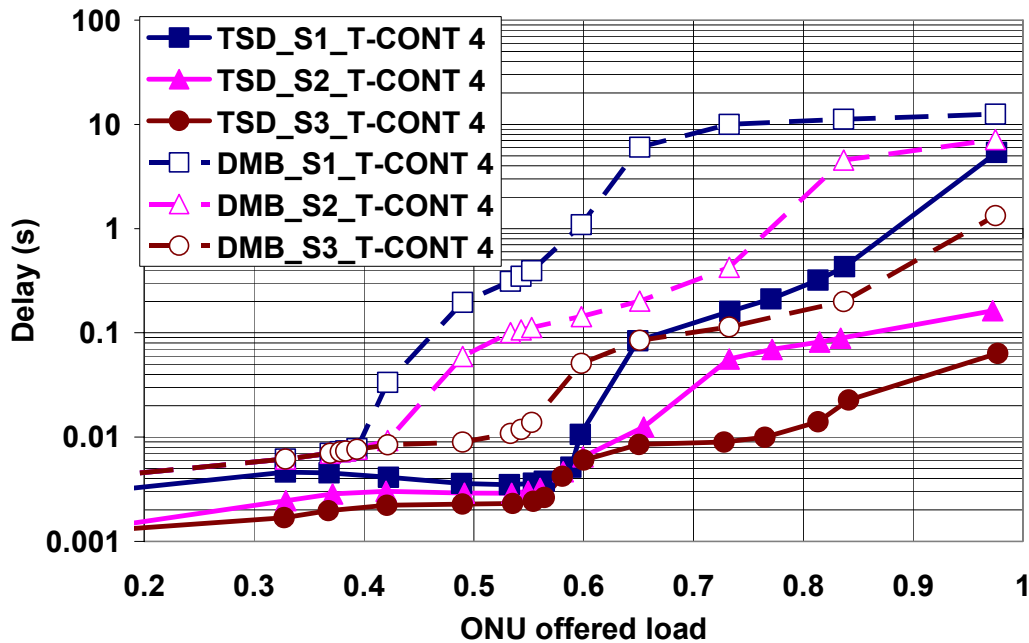


Figure 6-8 Mean packet delay for T_CONT 4 services under 3 kinds of ONU service levels in TSD and DMB

As illustrated in Chapter 2, in addition to mean packet delay performance for different ONU loads, the network packet loss rate is another critical measure to guarantee QoS for each T-CONT traffic. Since time sensitive traffic, T-CONT 2, can always be communicated with low packet delay, no packet loss is displayed in either protocol, focussing the TSD protocol loss rate performance evaluation to T-CONT 3 and 4 traffic characteristics, presented in Figure 6-9 and Figure 6-10 correspondingly. For T-CONT 3 traffic, considering the worst case scenario SL₁ ONUs, the loss-free transmission is extended from 950 Mbit/s ($1000 \text{ Mbit/s} \times 0.95$) with DMB to 1330 Mbit/s ($1000 \text{ Mbit/s} \times 1.33$) in TSD providing extra 380 Mbit/s network capacity to ISPs.

Similarly, the loss-free transmission for the time-insensitive traffic, T-CONT 4, is still extended from 670, 780 and 950 Mbit/s to 950, 1040 and 1340 Mbit/s providing an extra 280, 260 and 390 Mbit/s network capacity for SL₁, SL₂ and SL₃ respectively.

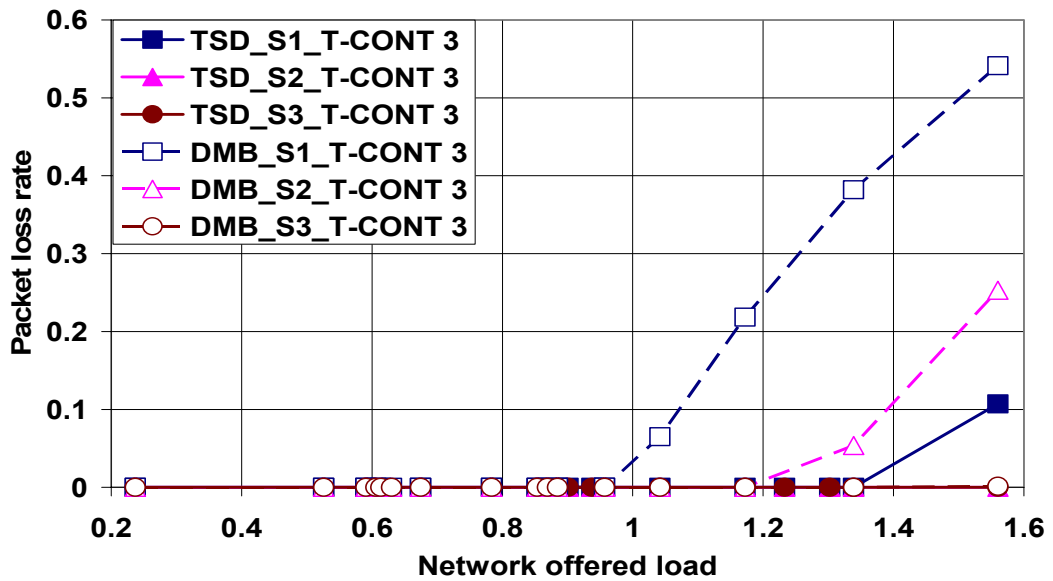


Figure 6-9 Mean packet loss rate for T-CONT 3 services under 3 kinds of ONU service levels in TSD and DMB

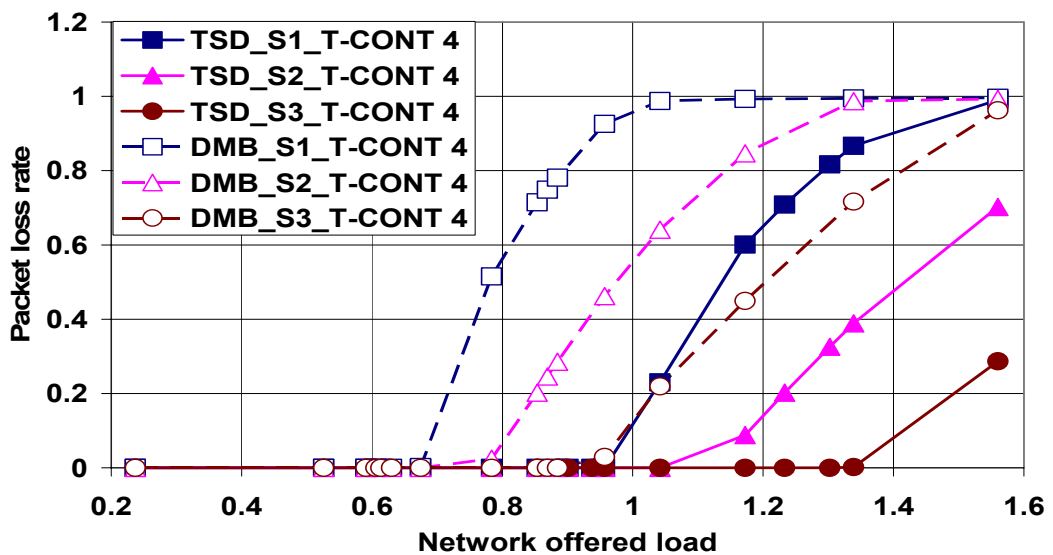


Figure 6-10 Mean packet loss rate for T-CONT 4 services under 3 kinds of ONU service levels in TSD and DMB

6.4 Summary

By reason of extending the PON application to terminate widely scattered subscribers effectively in a combined access/metro network and subsequently considerably reduced the number of COs, this chapter has described and demonstrated the performance of a novel algorithm which exhibits service level and CoS differentiation with highly efficient bandwidth assignment for a 100km-reach, 16-split GPON. In particular, the dynamic TSD protocol manages to overlap the idle time-slots in each data transmission cycle with a virtual polling cycle to increase the effective transmission bandwidth by means of a prediction method to estimate the bandwidth requirement of each ONU. Network performance investigations of the TSD scheme versus a developed algorithm have displayed significant 300 Mbit/s increase in channel throughput with an improvement in packet delay and packet loss rate to allow high network utilisation rates over extended network loads.

In particular the displayed 30 times reduction in mean packet delay for SL₁ ONUs at accustomed 50% ONU load constitutes the highest improvement of GPON overall packet delay reported up to date. It is also demonstrated that by considering the CoS in the ONUs, a low delay transmission is achieved for the time sensitive traffic, T-CONT 2, presenting the ability of the algorithm to support high QoS for this kind of services, such as VoD or HDTV, under any network offered load condition. Additionally, a maximum 70 and 12 times reduction in packet delay are achieved for T-CONT 3 and 4 traffic respectively demonstrating the advancements of the TSD protocol to efficiently and flexibly arrange the network capacity to support more multimedia services into the network. All of the improvements have demonstrated comparable achievements in terms of channel utilisation rate, packet delay and packet loss rate to standard access PONs at a superior 400% wider network coverage.

Chapter 7

Dynamic Bandwidth Allocation Protocol in Loop-back WDM-PONs

In single wavelength TDM protocols, the network capacity for each transmission direction is fixed and can not be distributed between them. To overcome the unavoidable network congestion of time-sharing PONs and provide end users with more bandwidth, a DBA protocol is presented in this chapter to distribute multi-wavelength PONs' upstream and downstream propagation capacity on demand. Network modeling by means of a loop-back WDM-PON architecture has demonstrated increased network utilization in contrast to standard TDM-PONs.

7.1 Introduction

Following the application of emerging applications, such as HDTV, VoD and online contents generation, the bandwidth demand for transmission is expected to eventually exceed the limited capacity of time-sharing topologies [15, 19, 44], forcing ISPs to gradually upgrade their network capacity. Although WDM topology is foreseen as the ultimate solution in that direction the cost of deploying WDM-PONs, primarily by means of fixed-wavelength ONUs, has currently limited international support in nominating them the major technology to provide near future FSAN networks. In consequence research initiatives have proposed the use of colourless ONUs that can be employed universally in TDM and WDM-PON architectures, by comprising RSOAs to display both downstream detection and upstream modulation of continuous waves (CWs) originating at the

OLT, avoiding the necessity of a wavelength-specific, local optical source [70] in a loop-back WDM-PON architecture [15, 19]. By means of the MAC layer the use of a reflective device in each ONU allows for centralised control in the OLT for both upstream and downstream and consequently dynamic sharing of bandwidth among the two transmissions according to ONU capacity requirement and service provisioning [70]. In the first stage of deploying such network, only one TL would be able to dynamically distribute bandwidth among ONUs. Once the bandwidth demand exceeds the network capability, the scalable network capacity can be doubled by adding an extra TL in the OLT [143].

Because of the reflective property of the ONUs, each transmitted frame from the OLT will comprise two sections, i.e. downstream data section and un-modulated CW section. As shown in Figure 2-8, on completion of downstream data detection, ONUs are expected to switch to transmission mode by modulating the CWs with upstream data [70]. In the loop-back WDM-PON topology, both upstream and downstream transmission optical carriers are provided by the same TLs in the OLT. Compared to typical TDM-PONs, the ONUs in the architecture, apart from sharing the upstream channel in time, will be also time-sharing the optical source to allocate bidirectional bandwidth on demand. Since time is the common dimension for allocating bandwidth in both technologies, the developed TDM protocols can act as references to originate the development of a multi-wavelength dynamic bandwidth allocation protocols for the reflective WDM-PONs.

In chapter 4, a novel DMB allocation protocol [117] has demonstrated QoS and differential-services. In expanding the TDM-based DMB protocol to provide an accurate time-slots arrangement for the loop-back WDM-PONs, the TL wavelength tuning time and RTT are investigated and presented in this chapter to develop a differential-services, multi-wavelength DMB (MDMB) algorithm with increased capacity utilisation.

7.2 Development of a WDM-based DBA Protocol

In the DMB algorithm, the OLT automatically assigns to each ONU a guaranteed minimum bandwidth, B_{min}^t , from the overall network capacity, to satisfy its basic service requirement at various service levels, t . Furthermore, the OLT apportions any unused bandwidth as an extra assigned bandwidth, $B_{ex_assigned}$, to ONUs according to their buffer queuing status. As shown in eq.4-7 for service level t , the maximum allocated bandwidth for ONU _{i} will be equal to the summation of B_{min}^t and $B_{ex_assigned}$. Otherwise, the allocated bandwidth, $B_{allocated}^i$ will be equal to R_i , if the bandwidth requirement, R_i , is smaller than the maximum allocation bandwidth [117].

Likewise, all developed single wavelength algorithms, the DMB is mainly used to arrange upstream transmission bandwidth only, but the downstream and upstream bandwidth in the reflective WDM-PON topology should be considered as an integrated parameter. As a result, the bandwidth requirement, R_i , in eq.4-7 should be replaced by the total bandwidth requirement, R'_i , for ONU _{i} in both directions as shown in eq. 7-1. Consequently the calculated assigned bandwidth for each ONU, $B_{allocated}^i$, needs to be redistributed between the downstream and upstream transmissions.

$$R'_i = R_{down}^i + R_{up}^i \quad (7-1)$$

The OLT frame in a reflective WDM-PON topology displays, as already mentioned, time-slots occupied by either downstream data or un-modulated CWs. In addition to synchronise packet transmission at each ONU receiver and reserve a suitable time span for the TL to change its emission wavelength, a guard time, T_{laser} , needs to be allocated at the start of each frame, as shown in Figure 2-8, that equals at least the summation of TL tuning time, preamble time and delimiter time at the beginning of each downstream frame. Furthermore, if the RTT difference between two consecutive ONUs ($i, i+1$) is longer than the summation of T_{laser} and the downstream transmission length, T_{down} , of ONU _{i} , the excess time length needs

to be added to T_{laser} to avoid data collision at the OLT receiver. On detection of downstream data, the ONU will switch to upstream transmission by modulating upstream data onto the CWs [70]. In that sense, depending on the switching speed of ONU electronics and the packet synchronisation speed at the OLT receiver, an extra guard time, T_{guard} , needs to be added between the downstream data and CWs time-slots to allow switching of ONU operation between the two modes.

7.2.1 The Polling Steps of the Multi-wavelength Bandwidth Allocation Protocol

As soon as the OLT has received in a cycle all report messages from ONUs, the new polling cycle starting time in a multi-wavelength scheme needs to be defined carefully to reserve a guard time for the TL to complete its previous cycle transmission. As shown in Figure 7-1, if the RTT of the last ONU in a polling cycle is longer than its upstream transmission period, its report message will reach the OLT after the TL has transmitted the CWs for that ONU. As a result, the new cycle starting time in this scenario will be defined at the instant right after the OLT has finished calculating the assigned bandwidth for all ONUs. Otherwise, the report message from the last ONU will reach the OLT before the TL has finished CW transmission. In that sense, the new polling cycle can not start until the TL has communicated the CWs corresponding to the last ONU of cycle n and has tuned its emission wavelength to activate the first ONU in the next polling cycle.

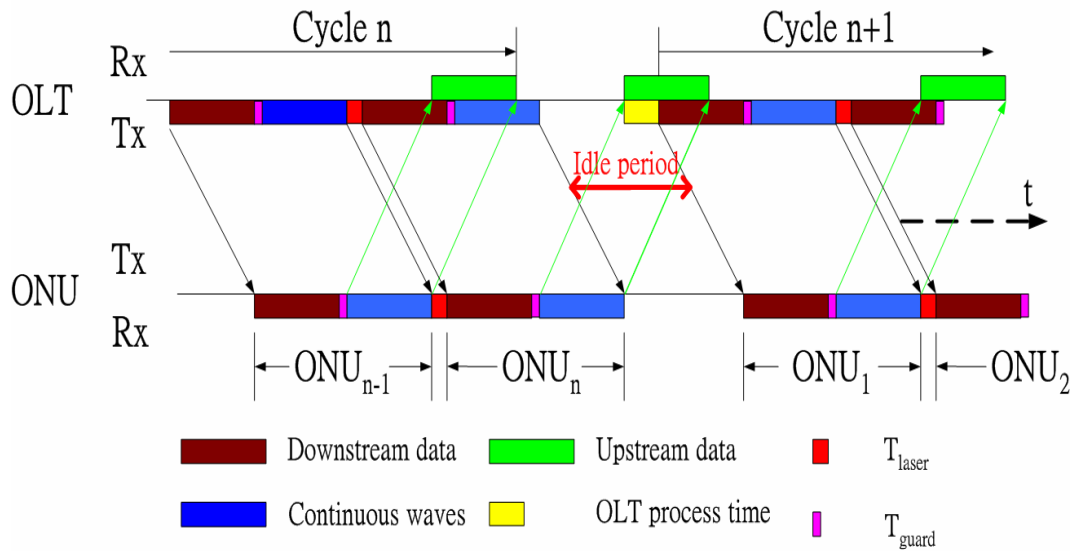


Figure 7-1 MDMB polling diagram

After the cycle starting time has been determined, the downstream and upstream time-slots can be arranged by the MDMB protocol according to ONUs' bandwidth requirements and service levels. If the summation of each ONU bandwidth requirement, R'_i from eq.7-1, is smaller than the available bandwidth, the OLT will fully satisfy each bandwidth demand and process transmission according to the following steps:

- A. Add a guard time, T_{laser} , for the TL to switch between wavelengths, to synchronise packet transmission at ONU receiver and to prevent the upstream data collision in the OLT receiver.
- B. Assign and transmit the downstream data for the first ONU.
- C. Add another guard time, T_{guard} , at the end of the downstream transmission to compensate for the ONU electronics switch time and synchronise packet transmission at the OLT receiver.
- D. Produce a period of CWs for the ONU to communicate its upstream data according to bandwidth demand.

E. Repeat steps 1 to 4 for the next ONU transmission.

On the other hand, if the overall bandwidth requirement temporarily exceeds the network capacity, an additional mechanism needs to be employed to define the amount of bandwidth between each transmission direction. Nevertheless, due to the absence of such mechanism in the initial development of the MDMB protocol, the network capacity has been utilised to fully satisfy downstream transmission and subsequently the remaining available bandwidth, B_{av_up} , is employed to transmit upstream data. As a result, B_{av_up} is distributed among ONUs by using the DMB algorithm in accordance with their service level and upstream bandwidth requirement.

7.3 The MDMB Model Implementation and Analysis

To evaluate the network performance, a reflective WDM-PON model, comprising a single OLT and 16 ONUs has been devised in OPNET Modeler. Due to the different topology in comparison to a TDM model, aspects of the initially developed simulation platform had to be modified and a new project editor implemented. As presented in Figure 7-2, a logical point-to-point WDM-PON structure can be represented by a star topology with the functionalities of each node described as follows:

- The downstream data source: Depending on network application, this node contains multiple OPNET data generator modules to sustain various traffic characteristics.
- The OLT: The major functionalities of the node are to define the number of ONUs connected to the network, process the integrated MAC protocol for data exchange and finally gather the transfer statistics.

- The ONU: Apart from gathering CPE statistics, it is designed to record the buffer queuing status and transmit data at designated upstream time-slots.

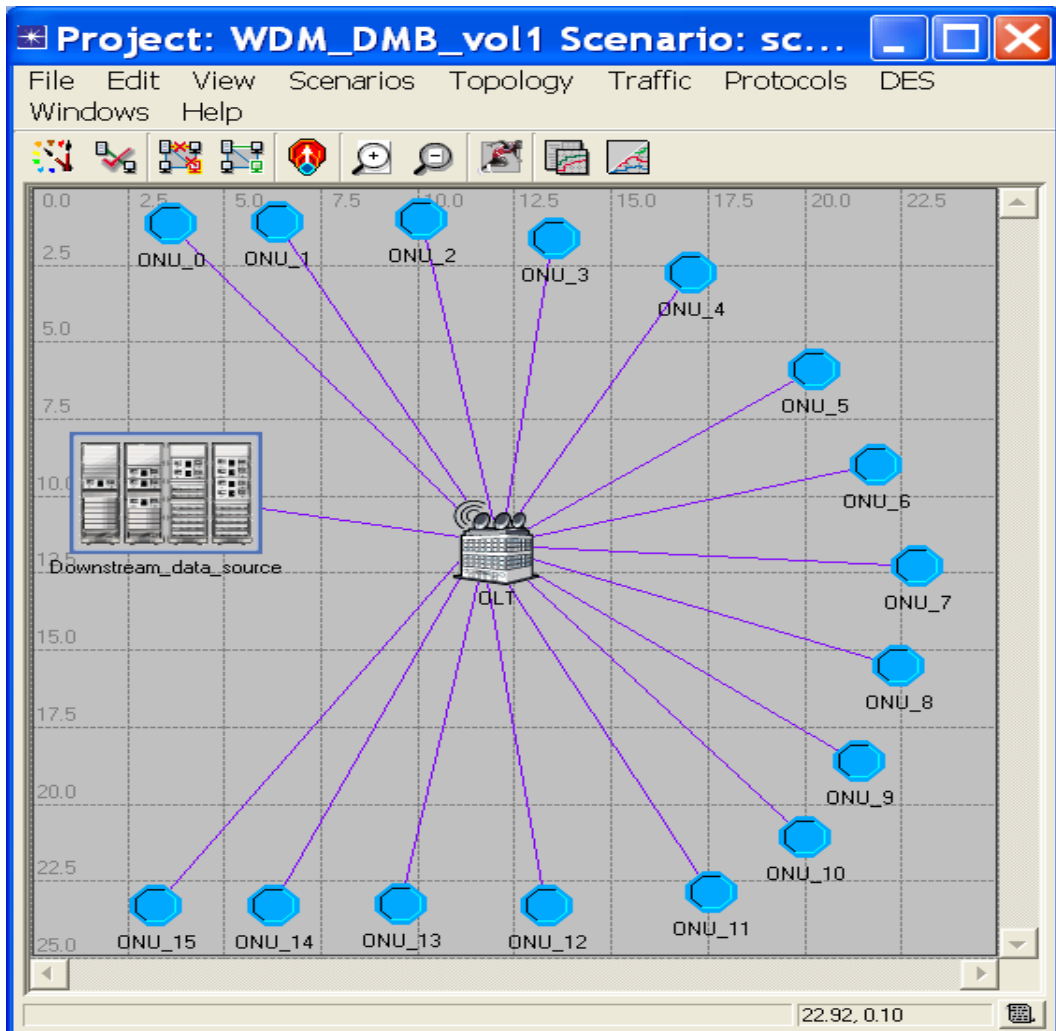


Figure 7-2 logical loop-back WDM PON model

The operation principles of the OLT and ONUs nodes in the loop-back WDM-PON model are alike the TDM-GPON model. The main difference is the provision of dedicated links to communicate each ONU's data to and from the OLT. Therefore the logical infrastructure of the OLT model in the WDM model presented in Figure 7-3, is composed of multiple transceiver pairs to establish communication between individual OLT-ONU links. Also since the logical operation of the ONU model in the GPON and WDM-PON platforms is identical, the ONU node model is not changed.

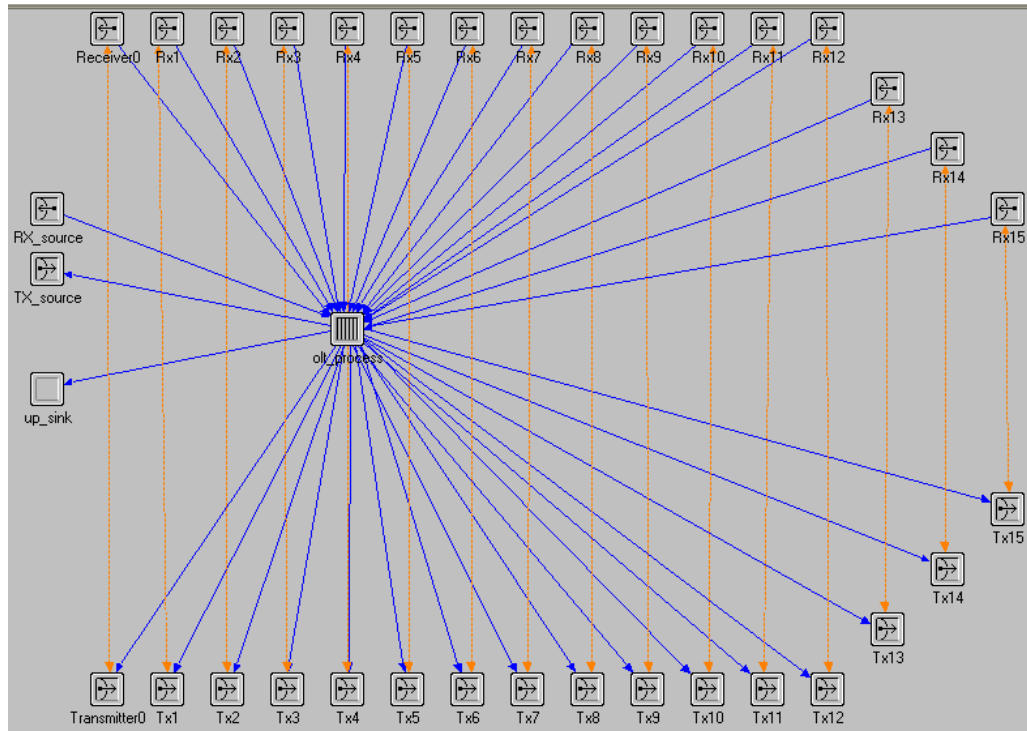


Figure 7-3 OLT node model in loop-back WDM-PON model

7.3.1 Simulation Test Bed Scenarios

To simulate a pragmatic network scenario, two ONUs in the WDM-PON model are set to operate at the highest service level, SL_3 , six at medium service level, SL_2 and eight at the lowest service level provisioning, SL_1 . Each ONU in the model is assigned to a maximum channel capacity of 100 Mbit/s at a fixed 2.48 Gbit/s aggregate data rate over 20 km link lengths [115]. In addition, a 2 ms maximum cycle period, 72 ns T_{laser} , and 56 ns T_{guard} are chosen according to the GPON standard [28] and the characteristics of commercial TLs [33, 68] to establish reliable data transfer between the OLT and ONUs.

To compare and contrast the bandwidth allocation efficiency of the MDMB with the DMB, the upstream transmission performance is monitored by fixing the overall downstream traffic load in succession to 528 Mbit/s, 800 Mbit/s and 1240 Mbit/s to simulate a practical service demand from low to high utilisation

respectively. These overall downstream traffic load figures correspond to fixed downstream traffic load for each MDMB ONU at 33 Mbit/s, 50 Mbit/s and 77.5 Mbit/s respectively while gradually increasing each time the upstream traffic load using a Pareto self-similar traffic model with a typical Hurst parameter of 0.8 to simulate practical network patterns [85].

In assigning the overall propagation capacity per ONU, the downstream requirement in bandwidth to guarantee QoS was initially satisfied, to comply with the typical assignment protocol in currently deployed GPONs/EPONs and dynamically allocate each time the remaining capacity in upstream. Since the 2.48Gbit/s maximum aggregate capacity in the modelled WDM-PON is parted between upstream and downstream, for the MDMB algorithm to provide increased utilization efficiency compared to the DMB algorithm, the measured upstream channel throughput should exceed the maximum possible 1.24 Gbit/s of the later.

7.3.2 Simulations and Performance Analysis

To compare and contrast the bandwidth allocation efficiency of the MDMB and DMB algorithms, initial simulations have considered 1240 Mbit/s overall downstream traffic loading. The simulated upstream channel throughput and mean packet delay characteristics are shown in Figure 7-4 and Figure 7-5 respectively for gradual increments of the upstream traffic load.

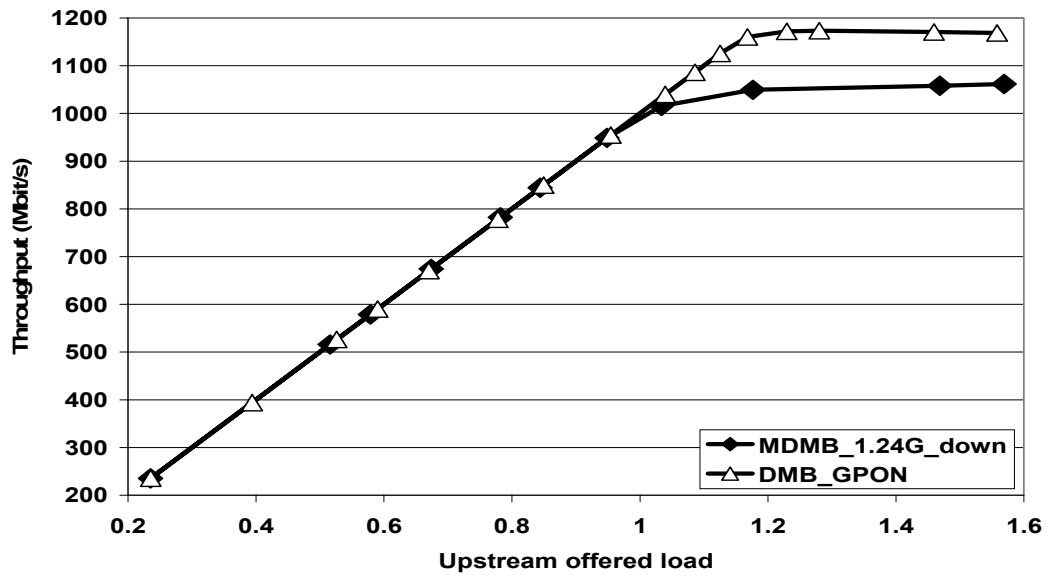


Figure 7-4 Upstream channel throughput for DMB and MDMB under fixed 1.24Gbit/s downstream loading

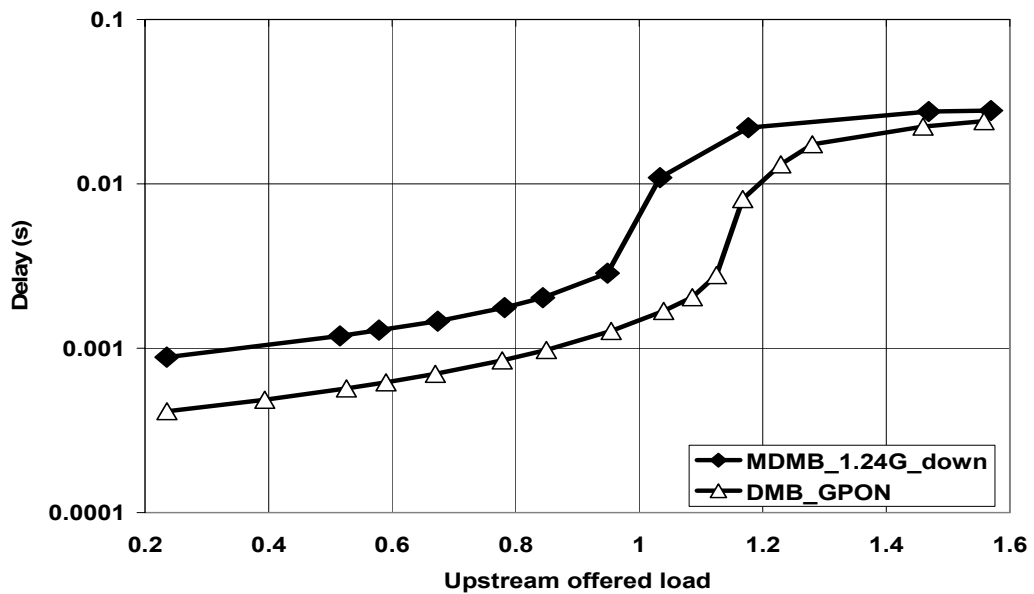


Figure 7-5 Mean upstream packet delay for DMB and MDMB under fixed 1.24Gbit/s downstream loading

It is apparent from the simulation results that the network performance in this extreme scenario for both evaluation measures displays increased efficiency in the application of the DMB protocol. This characteristic was largely expected considering the specific downstream utilisation since the upstream and

downstream bandwidth allocation in DMB is independent and due to the operating principle of the MDMB algorithm by which the network capacity is firstly utilised to accommodate downstream transmission and accordingly upstream propagation. In addition, the grant/report messages propagation time, T_{guard} and T_{laser} in each cycle engage transmission time-slots depending on the number of active ONUs, the operating specifications of OLT and ONU components, and ONU bandwidth requirements in each polling cycle. As a result, the maximum upstream throughput has been measured to reach 1.05 Gbit/s.

Nevertheless, the downstream traffic scenario considered so far represents considerably heavy downstream loading which does not fully characterise a realistic network usage of currently deployed, or near future PON infrastructures. This is true since burst-mode, real-time servicing, such as online gaming and HDTV are not currently of constant use of installed-base network resources. In a more realistic scenario the downstream capacity reserved for high bandwidth service provisioning in every polling cycle typically reach 50% of a given ONU capacity. In that sense, the maximum upstream network capacity in MDMB can be dynamically increased in every polling cycle rather than fixed at a constant value, like in DMB, to resourcefully improve the upstream transmission performance. In addition an enhanced MDMB protocol design is expected to account for increased downstream loading to comply with future network penetration, as described in the following chapter.

To observe the protocol performance for alternative upstream/downstream allocations, overall downstream rates of 528 Mbit/s and 800 Mbit/s have also been considered to simulate practical service demand, corresponding to 33 Mbit/s and 50 Mbit/s downstream ONU traffic load respectively.

The upstream channel throughput characteristics for all three scenarios are summarised in Figure 7-6. It becomes apparent that for the MDMB protocol the measured value expands from 1.05Gbit/s to 1.5Gbit/s up to a maximum of 1.56Gbit/s at 1240Mbit/s, 800 Mbit/s and 528 Mbit/s downstream traffic load

respectively. This translates to a 128% upstream network efficiency compared to 94% in the DMB protocol at a current development scenario, 33 Mbit/s ONU downstream service demand shown by the WDM_528M_down plot.

Similarly for the same 33 Mbit/s ONU downstream service demand scenario, the mean upstream packet delay performance in Figure 7-7 displays clearly that the MDMB protocol achieves QoS, specified at 5ms maximum packet delay in the GPON standard for time sensitive services [115], for upstream network load extending to 1.6 Gbit/s in contrast to the limited, 1.15Gbit/s DMB algorithm demonstrating the MDMB algorithm's ability to accommodate multimedia servicing.

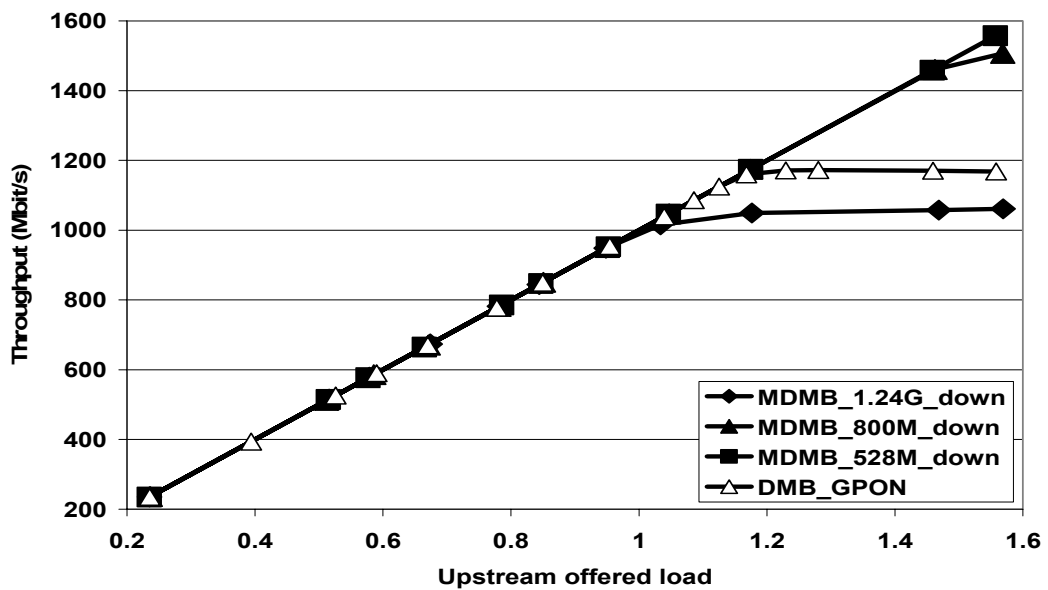


Figure 7-6 Upstream channel throughput for DMB and MDMB under fixed 1.24Gbit/s, 800 Mbit/s and 528 Mbit/s downstream loading

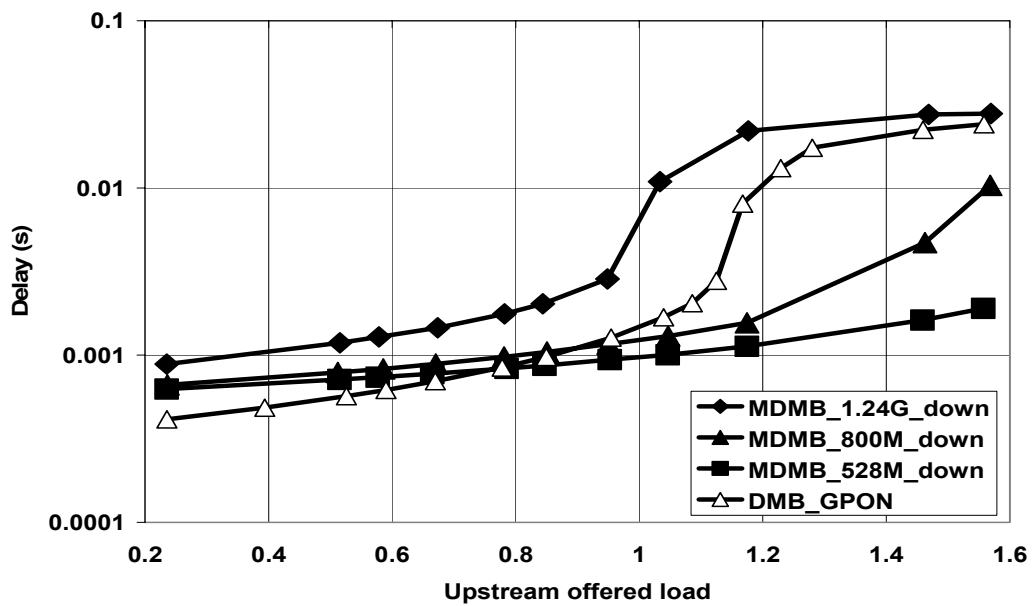


Figure 7-7 Mean upstream packet delay for DMB and MDMB under fixed 1.24 Gbit/s, 800 Mbit/s and 528 Mbit/s downstream loading

In addition, recorded packet loss rates in Figure 7-8 confirm the maximum throughput achieved by MDMB with no loss, is extended to 1.46 Gbit/s and around 1.6 Gbit/s at middle and low downstream traffic load scenarios respectively in contrast to 1.12 Gbit/s attained using DMB.

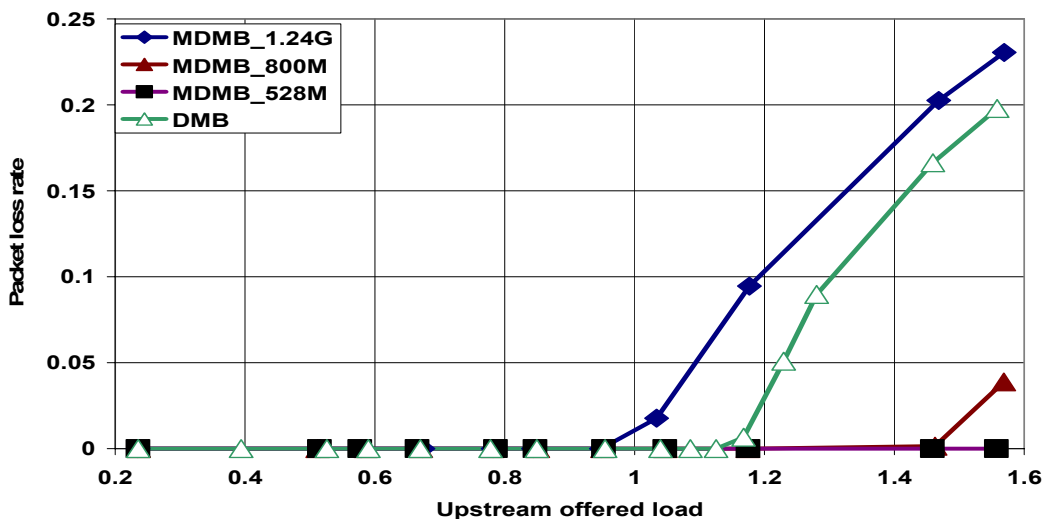


Figure 7-8 Mean upstream packet loss rate for DMB and MDMB under fixed 1.24 Gbit/s, 800 Mbit/s and 528 Mbit/s downstream loading

7.4 Summary

This chapter has demonstrated the development of a newly developed MDMB protocol to exhibit dynamic bandwidth assignment in reflective WDM-PONs. The use of RSOAs in the network ONUs allows for centralised control in the OLT for both upstream and downstream and consequently dynamic sharing of bandwidth among the two transmissions according to ONU capacity requirement and service provisioning. To accomplish this, the OLT initially integrates each ONU's upstream and downstream capacity requirement to compute their overall assigned bandwidth and subsequently dynamically distribute it between downstream and upstream directions by flexibly adjusting downstream frame time-slots reserved for each transmission propagation.

To contrast the upstream performance of the MDMB scheme to an already developed DBA algorithm, demonstrating high network utilisation in standard TDM-PONs, the overall downstream traffic load is fixed in sequence to three practical service demand scenarios. Consequently, network modelling has revealed 128% upstream network efficiency, compared to 94% in the DMB protocol at a currently developed 33 Mbit/s downstream access scenario. Similarly, for the same network specification, the proposed protocol has obtained mean upstream packet delay performance of less than 5ms which allows the network to maintain QoS for time-sensitive services at an ONU load reaching 100% of its upstream load capacity.

Chapter 8

Conclusions and Future Directions

This chapter serves the purpose of summarising the achievements accomplished in the course of this research programme in MAC protocol development to demonstrate dynamic bandwidth and wavelength assignment over GPONs, long-reach PONs and multi-wavelength PONs. Upstream bandwidth map enhancements to account for the application of multiple wavelength operation over standard splitter-based GPONs and the extension of the existing DBA algorithms to model increased data-rate, service-oriented propagation constitute immediate future developments.

8.1 Thesis Review

This thesis has illustrated a variety of novel single/multiple wavelength bandwidth allocation protocols for GPONs, long-reach PONs and WDM-PONs to resourcefully and dynamically arrange the bandwidth among subscribers.

The emergence of new bandwidth-intensive applications articulated by distance learning, online gaming, Web 2.0 and movie delivery by means of high-definition video, has ultimately justified the necessity of upgrading the access network infrastructure to provide fat-bandwidth pipelines at subscriber close proximity. PONs offer currently more opportunities to communicate these services than ever before, with potential connection speeds of up to 100 Mbit/s in mind [17]. PON-based access networks envisage the demonstration of scalability to allow gradual deployment of time and wavelength multiplexed architectures in a

single-platform without changes in fibre infrastructure and also highly-efficient bandwidth allocation for service provision and upgrade on-demand. Among various potential architectures, a scalable multi-PON access network architecture [18] has been proposed in that direction to provide interoperability among dynamic TDM and WDM-PONs through coarse-WDM routing in the OLT. To provide bandwidth on demand in such architectures, a novel TDM-DMB allocation protocol and an upgraded version have been presented in this thesis to achieve QoS at three different service levels and diverse network throughputs [117]. By considering the SLA into these two TDM-based algorithms, the OLT is able to intelligently distribute the network capacity among ONUs to guarantee QoS according to their SLA. These algorithms can detect excessive usage of bandwidth among customers and re-allocate the network bandwidth distribution based on their priority levels and request. Therefore, low priority clients can not use unfairly large amount of bandwidth when such requests compromise the services for high priority clients.

In view of the MAC layer of a typical 100 km long-reach TDM-PON, the direct implementation of the DMB protocol has displayed limited performance in terms of bandwidth utilisation due to a recorded, 500 μ s increase in packet propagation time compared to 25km-PONs, exhibiting a total of 1000 μ s-wide idle time-slots in each transmission cycle. To achieve acceptable channel throughput and packet delay performance, an innovative TSD protocol has been demonstrated that utilises the idle time-slots in the sense of virtual polling cycles, during which the ONUs can transmit data by means of a prediction method estimating their bandwidth requirement [80].

In addition, to allow for WDM-PON resource allocation, to overcome the inevitable network congestion of single wavelength networks, the developed MAC protocols have been extended to implement logical point-to-point topologies based on general loop-back WDM-PON architectures [144] to increase service provisioning between reflective ONUs and the OLT by vigorously

distributing network capacity simultaneously between the upstream and downstream.

8.2 Summary of Contributions

To allow centralised, dynamic bandwidth allocation in TDM-PONs, the OLT according to the developed algorithms assigns varying frame time-slots, initially to each PON in order-of-demand and subsequently arrange each PON bandwidth among their ONUs based on their service level and individual bandwidth requirement [87, 117]. In that direction, the DMB protocol [117] provides ONUs in TDM-PONs with three service levels at different weights, W_t , to represent network accessing priority. Subsequently the algorithm automatically assigns to each ONU a guaranteed minimum bandwidth, B_{min}^t , from the overall network capacity, to satisfy their basic service requirements at various service levels t and apportions any unused bandwidth to ONUs according to their buffer queuing status. Following probable variations in network capacity, it is capable of readjusting the guaranteed minimum and unused bandwidths among ONUs to comply with subscriber contracts. For service level t , for example the maximum allocated bandwidth $B_{max_allocated}$ for ONU _{i} will be equal to the addition of B_{min}^t and the extra assigned bandwidth, $B_{ex_assigned}$. Otherwise, if the bandwidth requirement, R_i , is smaller than the total, $B_{max_allocated}$ will be equal to the required bandwidth, R_i , as given by eq. 4-7.

To further reduce the packet waiting time in the ONUs, the network traffic self-similarity characteristics have been incorporated into the DMB protocol [87]. In addition, since the upstream and downstream channels are independent, the grant messages for subsequent polling cycles can be communicated before the last ONU has finished its upstream transmission. Consequently the OLT in what is known as the advanced DMB (ADMB) protocol possess the capability to automatically re-arrange the upstream transmission order by assigning the ONU with the longest upstream transmission period to the last upstream time-slot,

reducing the idle period and increasing the overall network throughput. Contrasting the ADMB protocol with published dynamic bandwidth assignment algorithms, simulation results have shown substantial reductions in mean packet delay [87], particularly at high network load in relation to the IPACT algorithm [85].

As presented in Figure 5-7, it is also demonstrated that by adjusting the effective upstream transmission order of the network ONUs, the maximum network throughput in the ADMB protocol can be significantly increased to fully utilise the available bandwidth for different traffic loads.

To achieve acceptable channel throughput and packet delay performance in typical 100 km long-reach TDM-PON, an innovative TSD protocol has been demonstrated that utilises the idle time-slots in the sense of virtual polling cycles, during which the ONUs can transmit data by means of a prediction method estimating their bandwidth requirement [80]. The amount of virtual bandwidths, allocated to ONUs, are determined by the DMB algorithm with each estimated ONU bandwidth requirement and 1000 μ s idle period regarded as the maximum polling period parameter [80]. As a result, simulation results have presented comparable network performance in terms of channel utilisation rate, packet delay, and packet loss rate to standard access PONs at a superior 400% wider network coverage [80].

Progressively, a WDM bandwidth allocation protocol has also been investigated to control simultaneously upstream and downstream data transfer. In accordance with the reflective multi-wavelength DMB (MDMB) protocol, OLT frames display time-slots occupied by either downstream data or un-modulated continuous waves (CWs) and unlike TDM-PON algorithms, where only the ONU upstream time-slots are considered, each ONU bandwidth requirement, R_i , as given in eq. 4-7 should be replaced by their bidirectional bandwidth requirement, R'_i , to account for both upstream and downstream. In addition the OLT assigned

bandwidth, $B^i_{allocated}$, should be consequently distributed between the upstream and downstream according to individual demand.

The upstream channel throughput characteristics for the contrasted protocols are shown in Figure 7-6. According to the WDM_528M_down response, representing the MDMB protocol throughput distribution for a typical 33 Mbit/s downstream ONU service demand, matching current TDM aggregate downstream rates, the recorded upstream throughput figure corresponds to approximately 1.6 Gbit/s. This translates to 128% upstream network efficiency compared to 94% achieved with the DMB protocol for TDM PONs.

8.3 Possible Applications and Future Directions

Recently, the 10Gbit/s Ethernet passive optical network (10GEAPON) is developing in IEEE P802.3av Task Force to provide point to multi-point connections with 10 Gbit/s downstream and 10 or 1 Gbit/s upstream data rates [24, 145]. By adjusting the transmission/acknowledgement packet formats, the DMB and ADMB protocols would be able to provide high efficient bandwidth arrangement with QoS and SLA provision.

In parallel, the demand for high data rate wireless connections has rapidly increased with radio-over-fibre technologies promising cost efficient transport of wireless signals over optical fibres [146-148]. In such system architectures, multiple subscribers are terminated to single base station ONUs demonstrating FTTC or FTTB equivalent infrastructures. Although different to a FTTH network topology and associated DBA protocols considered throughout this research, each ONU in a GPON network, according to the GPON standard G.984.3 [28], can be assigned with multiple logical IDs for different service applications. A FTTB or FTTC network can then be operated as a logical FTTH topology by assigning each wireless subscriber a logical ID. As a result, the transmission efficiency and QoS of wireless networking can be investigated in association with high

bandwidth optical provision by adapting the developed protocols to accommodate wireless standard transmission characteristics and modifying the project editors in OPNET to implement radio-over-fibre networking infrastructures [149-151].

With a different application in mind, the MDMB protocol in Chapter 7 is proposed to arrange data transmission in bandwidth scalable loop-back WDM-PONs. In the first stage of protocol development, the available network capacity has been primarily employed to accommodate downstream data transmission and sequentially upstream allocation based on the unused bandwidth. As a result, downstream servicing can be guaranteed with QoS while upstream traffic potentially undergo increased delay, particularly in the scenario of heavy network loading. Nonetheless, as discussed in chapter 2, the transmission conditions for different types of service are different.

To that extend, the performance of the MDMB protocol could be enhanced by dynamically reorganising capacity allocation between upstream and downstream. For example when T-CONT 4 traffic, such as FTP or web browsing, is to be serviced in downstream the initially allocated bandwidth could be transferred to upstream to transmit T-CONT 2 traffic, such as HDTV or VoD if necessary. Thus, another mechanism should be developed and adapted into the MDMB protocol to flexibly adjust the downstream and upstream capacities according to instant bandwidth requirements dictated by the presence of individual CoS. It is anticipated that the further research of the single/multiple wavelength MAC protocols will continually assist the development of the next generation optical networks.

References

- [1] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited]," *Journal of Optical Networking*, vol. 4, pp. 737-758, 2005.
- [2] R. Ramaswami and K. N. Sivarajan, *Optical Networks a Practical Perspective 2nd ed*: Academic Press, 2002.
- [3] F. Effenberger, D. Clearly, O. Haran, G. Kramer, R. D. Li, M. Oron, and T. Pfeiffer, "An introduction to PON technologies," *Communications Magazine, IEEE*, vol. 45, pp. S17-S25, 2007.
- [4] IEEE 802.16 The Working Group for WLAN Standards, "Wireless Metropolitan Area Networks," 2005.
- [5] IEEE 802.11 The Working Group for WLAN Standards, "LAN/MAN Wireless LANs," 2005.
- [6] IEEE 802.16 Working Group on Broadband Wireless Access Standards, "Worldwide Interoperability for Microwave Access (WiMAX)," 2000.
- [7] ITU-T Recommendation G.992.5, "Asymmetric Digital Subscriber Line (ADSL) transceivers - Extended bandwidth ADSL2 (ADSL2plus)," 2005.
- [8] ITU-T Recommendation G.993.2, "Very high speed digital subscriber line transceivers 2 (VDSL2)," 2006.
- [9] IEEE 802.3ah, "Ethernet in the First Mile Task Force," 2004.
- [10] Y. Maeda, K. Okada, and D. Faulkner, "FASN OAM-WG and future issues for broadband optical access networks," *IEEE Communications Magazine*, vol. 39, pp. 126-132, 2001.
- [11] Full Service Access Network, "<http://www.fsanweb.org>."
- [12] I. Van de Voorde and C. Van der Plas, "Full service optical access networks: ATM transport on passive optical networks," *Communications Magazine, IEEE*, vol. 35, pp. 70-75, 1997.
- [13] S. R. Sherif, A. Hadjiantonis, G. Ellinas, C. Assi, and M. A. Ali, "A novel decentralized ethernet-based PON access architecture for provisioning differentiated QoS," *Journal of IEEE Lightwave Technology*, vol. 22, pp. 2483-2497, 2004.
- [14] D. Nowak and J. Murphy, "FTTH: The Overview of Existing Technologies," presented at SPIE Opto-Ireland: Optoelectronics, Photonic Devices, and Optical Networks, Dublin, 2005.
- [15] S.-J. Park, C.-H. Lee, K.-T. Jeong, H.-J. Park, J.-G. Ahn, and K.-H. Song, "Fiber-to-the-Home Services Based on Wavelength-Division-Multiplexing Passive Optical Network," *Journal of Lightwave Technology*, vol. 22, pp. 2582-2591, 2004.
- [16] C.-H. Lee, S.-M. Lee, K.-M. Choi, J.-H. Moon, S.-G. Mun, K.-T. Jeong, J. H. Kim, and B. Kim, "WDM-PON experiences in Korea [invited]," *OSA Journal of Optical Networking*, vol. 6, pp. 451-464, 2007.
- [17] P.-F. Fournier, "From FTTH pilot to pre-rollout in France," presented at Presented at CAI, Cheuvreux, France, 2007.

-
- [18] Y. Shachaf, C. H. Chang, P. Kourtessis, and J. M. Senior, "Multi-PON access network using a coarse AWG for smooth migration from TDM to WDM PON," *Journal of OPTICS EXPRESS*, vol. 15, pp. 7840-7844, 2007.
- [19] D. Gutierrez, K. S. Kim, S. Rotolo, F.-T. An, and L. G. Kazovsky, "FTTH standards, deployments and research issues (Invited paper)," presented at Joint Conference on Information Sciences (JCIS), Salt Lake City, UT, USA, 2005.
- [20] C.-H. Lee, W. V. Sorin, and B. Y. Kim, "Fiber to the Home Using a PON Infrastructure," *Journal of IEEE Lightwave Technology*, vol. 24, pp. 4568-4583, 2006.
- [21] E. Paul and J. Green, *Fiber to the Home: The New Empowerment*. New York: Wiley Interscience, 2005.
- [22] C.-H. Lee, "Passive optical networks for FTTx applications," presented at Optical Fiber Communication Conference (OFC/NFOEC), 2005, Anaheim, USA, 2005.
- [23] IEEE Ethernet in the First Mile Task Force Draft P802.3ah/D1.414, "Media Access Control Parameters, Physical Layers and Management Parameters for Subscriber Access Networks," pp. March, 2003.
- [24] IEEE P802.3av Task Force, "10Gb/s Ethernet Passive Optical Network (10GEPON)," IEEE, 2008.
- [25] F. a. BroadLight., "Comparing Gigabit PON Technologies ITU-T G.984 GPON vs. IEEE 802.3ah EPON," <http://www.broadlight.com/e-presenter/media/documents/GPON%20vs%20EPON.pdf>; 12-11-2004.
- [26] ITU-T Recommendation G.984.1, "Gigabit-capable Passive Optical Networks (GPON): General characteristics," 2003.
- [27] ITU-T Recommendation G.984.2, "Gigabit-capable passive optical networks (GPON): Physical media dependent (PMD) layer specification," 2003.
- [28] ITU-T Recommendation G.984.3, "Gigabit-capable passive optical networks (GPON): transmission convergence layer specification," 2005.
- [29] ITU-T Recommendation G.984.4, "Gigabit-Capable Passive Optical Networks (G-PON): ONT Management and Control Interface Specification," 2005.
- [30] S. Smith, "Business class services over a GPON network," presented at Optical Fiber Communication Conference and National Fiber Optic Engineers Conference (OFC/NFOEC), 2006, Anaheim, California, USA, 2006.
- [31] J. D. Angelopoulos, H.-C. Leligou, T. Argyriou, S. Zontos, E. Ringoot, and T. Van Caenegem, "Efficient transport of packets with QoS in an FSAN-aligned GPON," *Communications Magazine, IEEE*, vol. 42, pp. 92-98, 2004.
- [32] J. M. Senior, M. R. Handley, and M. S. Leeson, "Developments in wavelength division multiple access networking," *Communications Magazine, IEEE*, vol. 36, pp. 28-36, 1998.
- [33] Y.-L. Hsueh, M. S. Rogge, W.-T. Shaw, L. G. Kazovsky, and S. Yamamoto, "SUCCESS-DWA: a highly scalable and cost-effective optical

- access network," *Communications Magazine, IEEE*, vol. 42, pp. S24-S30, 2004.
- [34] M. P. McGarry, M. Reisslein, and M. Maier, "WDM Ethernet passive optical networks," *Communications Magazine, IEEE*, vol. 44, pp. S18-S25, 2006.
- [35] L. Wang, M. Hamdi, R. Manivasakan, and D. H. K. Tsang, "Multimedia-MAC Protocol: Its Performance Analysis and Applications for WDM Networks," *IEEE Transactions on Communications*, vol. 53, 2006.
- [36] J. Segarra, V. Sales, and J. Prat, "An All-Optical Access-Metro Interface for Hybrid WDM/TDM PON Based on OBS," *Journal of IEEE Lightwave Technology*, vol. 25, pp. 1002-1016, 2007.
- [37] A. R. Dhaini, C. M. Assi, M. Maier, and A. Shami, "Dynamic Wavelength and Bandwidth Allocation in Hybrid TDM/WDM EPON Networks," *Journal of IEEE Lightwave Technology*, vol. 25, pp. 277-286, 2007.
- [38] J.-M. Kang and S.-K. Han, "A novel hybrid WDM/SCM-PON sharing wavelength for up- and down-link using reflective semiconductor optical amplifier," *IEEE Photonics Technology Letters*, vol. 18, pp. 502-504, 2006.
- [39] A.-H. Kim, J.-H. Park, H.-S. Cho, and C.-H. Lee, "Laser spectral envelope control using a double contact fabry-Perot laser diode for WDM-PON," *IEEE Photonics Technology Letters*, vol. 18, pp. 2132-2134, 2006.
- [40] S.-B. Park, D. K. Jung, D. J. Shin, H. S. Shin, I. K. Yun, J. S. Lee, Y. K. Oh, and Y. J. Oh, "Demonstration of WDM-PON with 50 GHz channel spacing employing spectrum-sliced reflective semiconductor optical amplifiers," *Electronics Letters*, vol. 42, pp. 1172-1173, 2006.
- [41] K.-D. Langer, J. Vathke, K. Habel, and C. Arellano, "Recent Developments in WDM-PON Technology," presented at International Conference on Transparent Optical Networks (ICTON) 2006, Nottingham, United Kingdom, 2006.
- [42] C. Arellano, V. Polo, C. Bock, and J. Prat, "Bidirectional single fiber transmission based on a RSOA ONU for FTTH using FSK-IM modulation formats," presented at Optical Fiber Communication Conference (OFC/NFOEC), 2005, Anaheim, USA, 2005.
- [43] S.-M. Lee, K.-M. Choi, S.-G. Mun, J.-H. Moon, and C.-H. Lee, "Dense WDM-PON based on wavelength locked Fabry-Perot lasers," presented at Optical Fiber Communication Conference (OFC/NFOEC), 2005, Anaheim, USA, 2005.
- [44] F.-T. An, K. S. Kim, Y.-L. Hsueh, M. S. Rogge, W.-T. Shaw, and L. G. Kazovsky, "Evolution, challenge and enabling technologies for future WDM-based optical access networks," presented at 7th Joint Conference on Information Sciences (JCIS), North Carolina, USA, 2003.
- [45] M. Maier, M. Scheutzow, and M. Reisslein, "The arrayed-waveguide grating-based single-hop WDM network: an architecture for efficient multicasting," *IEEE Journal on Selected Areas in Communications*, vol. 21, pp. 1414-1432, 2003.
- [46] H. J. R. Dutton, "Understanding Optical Communications," *IBM Corporation, International Technical Support Organization*, 1998.

-
- [47] K. H. Han, E. S. Son, H. Y. Choi, K. W. Lim, and Y. C. Chung, "Bidirectional WDM PON using light-emitting diodes spectrum-sliced with cyclic arrayed-waveguide grating," *Photonics Technology Letters, IEEE*, vol. 16, pp. 2380-2382, 2004.
- [48] R. Roka, "The utilization of the DWDM/CWDM combination in the metro/access networks," presented at Joint First Workshop on Mobile Future and Symposium on Trends in Communications,(SymptoTIC), Bratislava, Slovak Republic, 2003.
- [49] O. Akanbi, J. Yu, G. Ellinas, and G.-K. Chang, "A Novel Scalable Multistage DWDM PON Architecture Using Cascaded Optical Interleavers With Increasing Periodicities Controlled in Central Offices," presented at Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference, OFC/NFOEC 2007., Anaheim, CA, USA., 2007.
- [50] C. Arellano, C. Bock, J. Prat, and K.-D. Ianger, "RSOA-based optical network units for WDM-PON," presented at Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference (OFC/NFOEC) 2006, Anaheim, California, USA., 2006.
- [51] B. S. Rho and J. W. Lim, "WDM-PON module using a planar lightwave circuit with a coated WDM filter," *IEEE Photonics Technology Letters*, vol. 18, pp. 1867-1869, 2006.
- [52] E. H. Lee, Y. C. Bang, J. K. Kang, Y. C. Keh, D. J. Shin, J. S. Lee, S. S. Park, I. Kim, J. K. Lee, Y. K. Oh, and D. H. Jang, "Uncooled C-band wide-band gain lasers with 32-channel coverage and -20-dBm ASE injection for WDM-PON," *IEEE Photonics Technology Letters*, vol. 18, pp. 667-669, 2006.
- [53] Y.-L. Hsueh, M. S. Rogge, S. Yamamoto, and L. G. Kazovsky, "A highly flexible and efficient passive optical network employing dynamic wavelength allocation," *Lightwave Technology*, vol. 23, pp. 277-286, 2005.
- [54] F.-T. An, K. S. Kim, D. Gutierrez, S. Yam, E. Hu, K. Shrikhande, and L. G. Kazovsky, "SUCCESS: A next-generation hybrid WDM/TDM optical access network architecture," *IEEE/OSA Journal of Lightwave Technology*, 2004.
- [55] K. S. Kim, D. Gutierrez, F.-T. An, and L. G. Kazovsky, "Batch scheduling algorithm for SUCCESS WDM-PON," presented at Global Telecommunications Conference (GLOBECOM). IEEE, Dallas, Texas USA, 2004.
- [56] E. S. Son, K. H. Han, J. K. Kim, and Y. C. Chung, "Bidirectional passive optical network for the transmission of WDM channels with digital broadcast video signals," *Optical Fiber Communication Conference (OFC)*, pp. 767-768, 2002.
- [57] N. Calabretta, M. Presi, R. Proietti, G. Contestabile, and E. Ciaramella, "A Bidirectional WDM/TDM-PON Using DPSK Downstream Signals and a Narrowband AWG," *IEEE Photonics Technology Letters*, vol. 19, pp. 1227-1229, 2007.

-
- [58] S.-M. Lee, M.-H. Kim, and C.-H. Lee, "Demonstration of a Bidirectional 80-km-Reach DWDM-PON With 8-Gb/s Capacity," *IEEE Photonics Technology Letters*, vol. 19, pp. 405-407, 2007.
- [59] J. Chen and L. Wosinska, "Performance Analysis of Protection Schemes Compatible with Smooth Migration from TDM-PON to Hybrid WDM/TDM-PON," presented at Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference, OFC/NFOEC 2007., Anaheim, CA, USA., 2007.
- [60] F. Clarke, S. Sarkar, and B. Mukherjee, "Simultaneous and interleaved polling: an upstream protocol for WDM-PON," presented at Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference (OFC/NFOEC) 2006, Anaheim, California, USA., 2006.
- [61] J. Kani, M. Teshima, K. Akimoto, N. Takachio, H. Suzuki, K. Iwatsuki, and M. Ishii, "A WDM-based optical access network for wide-area gigabit access services," *Communications Magazine, IEEE*, vol. 41, pp. S43-S48, 2003.
- [62] J. Kim, J. Cho, M. Kang, and H. Yon, "A dynamic bandwidth allocation protocol in WDM-PON with loop-back scheme," in *The 6th International Conference on Advanced Communication Technology (ICACT)*, vol. 1. Phoenix Park, Republic of Korea, 2004, pp. 69-71.
- [63] S.-B. Park, D. K. Jung, D. J. Shin, H. S. Shin, I. K. Yun, I. K. Yun, J. S. Lee, and Y. K. Oh, "Colorless Operation of WDM-PON Employing Uncooled Spectrum-Sliced Reflective Semiconductor Optical Amplifiers," *IEEE Photonics Technology Letters*, vol. 19, pp. 248-250, 2007.
- [64] J.-M. Kang, T.-Y. Kim, I.-H. Choi, S.-H. Lee, and S.-K. Han, "Self-seeded reflective semiconductor optical amplifier based optical transmitter for upstream WDM-PON link," *IET Optoelectronics*, vol. 1, pp. 77-81, 2007.
- [65] F. Payoux, P. Chanclou, and N. Genay, "WDM-PON with colorless ONUs," presented at Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference, OFC/NFOEC 2007, Anaheim, CA, USA., 2007.
- [66] M.-F. Huang, J. Yu, J. Chen, G.-K. Chang, and S. Chi, "A Cost-Effective WDM-PON Configuration Employing Innovative Bi-directional Amplification," presented at Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference, OFC/NFOEC 2007., Anaheim, CA, USA., 2007.
- [67] E. K. MacHale, G. Talli, and P. D. Townsend, "10 Gb/s bidirectional transmission in a 116 km reach hybrid DWDM-TDM PON," presented at Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference (OFC/ NFOEC) 2006, Anaheim, California, USA., 2006.
- [68] C. Bock and J. Prat, "Scalable WDMA / TDMA protocol for passive optical networks that avoids upstream synchronization and features dynamic bandwidth allocation," *Journal of Optical Networking*, vol. 4, pp. 226-236, 2005.
- [69] J. Segarra, C. Bock, and J. Prat, "Hybrid WDM/TDM PON based on bidirectional reflective ONUs offering differentiated QoS via OBS,"

- presented at Transparent Optical Networks, 7th International Conference, Barcelona, Catalonia, 2005.
- [70] J. Prat, C. Arellano, V. Polo, and C. Bock, "Optical network unit based on a bidirectional reflective semiconductor optical amplifier for fiber-to-the-home networks," *Photonics Technology Letters, IEEE*, vol. 17, pp. 250-252, 2005.
- [71] E. Wong, K.-L. Lee, and T. Anderson, "Low-cost WDM passive optical network with directly-modulated self-seeding reflective SOA," *Electronics Letters, IEE*, vol. 42, pp. 299-301, 2006.
- [72] C. Bock and J. Prat, "WDM/TDM PON experiments using the AWG free spectral range periodicity to transmit unicast and multicast data," *Optics Express*, vol. 13, pp. 2887-2891, 2005.
- [73] O. Akanbi, J. Yu, and G.-K. Chang, "A new scheme for bidirectional WDM-PON using upstream and downstream channels generated by optical carrier suppression and separation technique," *IEEE Photonics Technology Letters*, vol. 18, pp. 340-342, 2006.
- [74] N. Genay, P. Chanciou, R. Brenot, M. Moignard, and F. Payoux, "Colourless ONU modules in TDM-PON and WDM-PON architectures optical carrier remote modulation," presented at European Conference on Optical Communication (ECOC), 2005, Glasgow, UK., 2005.
- [75] J. Xie, S. Jiang, and Y. Jiang, "A dynamic bandwidth allocation scheme for differentiated services in EPONs," *Communications Magazine, IEEE*, vol. 42, pp. S32-S39, 2004.
- [76] G. Talli and P. D. Townsend, "Hybrid DWDM-TDM long-reach PON for next-generation optical access," *Journal of Lightwave Technology*, vol. 24, pp. 2827-2834, 2006.
- [77] I. T. Monroy, F. Ohman, K. Yvind, R. Kjaer, C. Peucheret, A. M. J. Koonen, and P. Jeppesen, "85 km Long Reach PON System Using a Reflective SOA-EA Modulator and Distributed Raman Fiber Amplification," *IEEE Lasers & Electro-Optics Society*, pp. 705-706, 2006.
- [78] R. Kjaer, I. T. Monroy, L. K. Oxenloewe, P. Jeppesen, and B. Palsdottir, "Bi-directional 120 km Long-reach PON Link Based on Distributed Raman Amplification," *IEEE Lasers & Electro-Optics Society*, pp. 703-704, 2006.
- [79] Darren P. Shea and J. E. Mitchell, "A 10-Gb/s 1024-Way-Split 100-Km Long-Reach Optical-Access Network," *Journal of IEEE Lightwave Technology*, vol. 25, pp. 685-693, 2007.
- [80] C. H. Chang, N. M. Alvarez, P. Kourtessis, and J. M. Senior, "Dynamic Bandwidth assignment for Multi-service access in long-reach GPON," presented at 33rd European Conference and Exhibition on Optical Communication (ECOC), Berlin, Germany, 2007.
- [81] ITU-T Recommendation G.984.5, "Enhancement band for gigabit capable optical access networks," 2007.
- [82] OPNET Modeler, "OPNET Technologies, Inc."
- [83] X.-Z. Qiu, P. Ossieur, J. Bauwelinck, Y. Yi, D. Verhulst, J. Vandewege, B. DeVos, and P. Solina, "Development of GPON Upstream Physical-Media-

- Dependent Prototypes," *Journal of Lightwave Technology*, vol. 22, pp. 2498-2508, 2004.
- [84] Y. Luo and N. Ansari, "Bandwidth allocation for multiservice access on EPONs," *Communications Magazine, IEEE*, vol. 43, pp. S16-S21, 2005.
- [85] G. Kramer, B. Mukherjee, and G. Pesavento, "IPACT a dynamic protocol for an Ethernet PON (EPON)," *Communications Magazine, IEEE*, vol. 40, pp. 74-80, 2002.
- [86] H. Miyoshi, T. Inoue, and K. Yamashita, "QoS-aware dynamic bandwidth allocation scheme in Gigabit-Ethernet passive optical networks," presented at IEEE International Conference on Communications (ICC), Paris, France, 2004.
- [87] C.-H. Chang, P. Kourtessis, and J. M. Senior, "Dynamic Bandwidth assignment for Multi-service access in GPON," presented at 12th European Conference on Networks and Optical Communications (NOC), Stockholm, Sweden, 2007.
- [88] ITU-T Recommendation G.983.4, "A broadband optical access system with increased service capability using dynamic bandwidth assignment," 2001.
- [89] J. Aheng and H. T. Mouftah, "Media Access Control for Ethernet Passive Optical networks: an overview," *IEEE Communications Magazine*, vol. 43, pp. 145-150, 2005.
- [90] Z. J., "Efficient Bandwidth Allocation Algorithm for Ethernet Passive Optical Networks," *Proceedings of IEE Communications*, vol. 153, pp. 464-468, 2006.
- [91] J. Zheng and H. T. Mouftah, "An Adaptive MAC Polling Protocol for Ethernet Passive Optical Networks," *Proceedings of IEEE ICC*, pp. 1874-1878, 2005.
- [92] J. D. Angelopoulos, I. S. Venieris, and G. I. Stassinopoulos, "A TDMA Based Access Control Scheme for APON's," *IEEE Journal of Lightwave Technology*, vol. 11, pp. 1095-1103, 1993.
- [93] J. D. Angelopoulos and et al., "A Transparent MAC Method for Bandwidth Sharing and CDV Control at The ATM layer of Passive Optical Networks," *IEEE Journal of Lightwave Technology*, vol. 14, pp. 2625-2635, 1996.
- [94] G. Kramer, B. Mukherjee, and G. Pesavento, "Ethernet PON (ePON): Design and Analysis of an Optical Access Network.," *Photonic Network Communications*, vol. 3, 2001.
- [95] G. Kramer and G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," *Communications Magazine, IEEE*, vol. 40, pp. 66-73, 2002.
- [96] Denis J. G. Mestdagh, *Fundamentals of Multiaccess Optical Fiber Networks*: Artech House, Inc., 1995.
- [97] F. Halsall, *Data Communications, Computer Networks and Open Systems fourth ed.* USA: Addison-Wesley, 1996.
- [98] D. J. Shin, D. K. Jung, H. S. Shin, J. W. Kwon, S. Hwang, Y. Oh, and C. Shim, "Hybrid WDM/TDM-PON With Wavelength-Selection-Free

- Transmitters," *Journal of Lightwave Technology*, vol. 23, pp. 187-195, 2005.
- [99] N. Zhang, M. Xu, R. Liao, H. Yoshiuchi, Y. Ji, and G. Saren, "A Service-Classified and QoS-Guaranteed Triple Play Mode in FTTH Network," presented at First International Conference on Communications and Networking in China, ChinaCom 2006, Beijing, China, 2006.
- [100] D. K. Mynbaev, "Analysis of quality of service provisioning in passive optical networks," presented at 2nd International Conference on Broadband Networks, 2005, Boston, Massachusetts, USA, 2005.
- [101] B. Mukherjee, "Optical Access Networks," 2004.
- [102] M. Ma, Y. Zhu, and T. H. Cheng, "A bandwidth guaranteed polling MAC protocol for Ethernet passive optical networks," *INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies. IEEE*, vol. 1, pp. 22-31, 2003.
- [103] H. Naser and H. T. Mouftah, "A fast class-of-service oriented packet scheduling scheme for EPON access networks," *IEEE Communications Letters*, vol. 10, pp. 396-398, 2006.
- [104] G. Kramer and B. Mukherjee, "Supporting differentiated classes of service in Ethernet passive optical networks," *Optical Networking*, vol. 1, pp. 280-298, 2002.
- [105] A. Nouroozifar, H. T. Mouftah, and H. Naser, "A novel differentiated scheduling algorithm for EPONs," *Proceedings of 2005 7th Transparent Optical Networks International Conference*, vol. 1, pp. 237-240, 2005.
- [106] N. Ghani, A. Shami, C. Assi, and M. Y. A. Raja, "Quality of service in Ethernet passive optical networks," *Advances in Wired and Wireless Communication, 2004 IEEE/Sarnoff Symposium on*, pp. 26-27, 2004.
- [107] G. Pesavento, "Ethernet Passive Optical Network (EPON) Architecture for Broadband Access," *Optical Networks Magazine*, 2003.
- [108] J. D. Angelopoulos and et al., "TDMA Multiplexing of ATM Cells in a Residential Access SuperPON," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1123-1133, 1998.
- [109] Y.-s. J. Osamu Yoshihara and Y.-s. J. Noriki Miki, "Dynamic Bandwidth Allocation Circuit, Dynamic Bandwidth Allocation Method, Dynamic Bandwidth allocation program and Recording Medium," Ho4J 3/16 ed. USA: Nippon Telegraph and Telephone Corporation, 2003.
- [110] N. Ghani, A. Shami, C. Assi, and M. Y. A. Raja, "Intra-ONU bandwidth scheduling in Ethernet passive optical networks," *Communications Letters, IEEE*, vol. 8, pp. 683-685, 2004.
- [111] D. Nowak, P. Perry, and J. Murphy, "Bandwidth Scheduling Techniques for Differentiated Services Support in Ethernet Passive Optical Networks," presented at 4th International Symposium on Communication Systemes, Networks and Digistal Signal Processing (CSNDSP), Newcastle, UK, 2004.
- [112] F.-T. An, Y.-L. Hsueh, K. S. Kim, I. M. White, and L. G. Kazovsky, "A new dynamic bandwidth allocation protocol with quality of service in Ethernet-based passive optical networks," *Technical Digest of OFC 2003*, 2003.

-
- [113] D. Nowak, P. Perry, and J. Murphy, "Bandwidth Allocation for Service Level Agreement Aware Ethernet Passive Optical Networks," in *Global Telecommunications Conference (GLOBECOM) IEEE*, vol. 3. Dallas, USA, 2004, pp. 1953-1957.
- [114] J. D. Angelopoulos, H.-C. Leligou, T. Argyriou, and S. Zontos, "Prioritized Multiplexing of Traffic Accessing an FSAN-Compliant GPON," *Lecture Notes in Computer Science (LNCS)*, vol. 3042, pp. 890-901, 2004.
- [115] A. Cauvin, J. Brannan, and K. Saito, "Common technical specification of the G-PON system among major worldwide access carriers," *Communications Magazine, IEEE*, vol. 44, pp. 34-40, 2006.
- [116] C. H. Chang, P. Kourtessis, and J. M. Senior, "Service level agreement based dynamic bandwidth allocation for GPONs," in *11th European Conference on Networks and Optical Communications (NOC)*. Berlin, Germany, 2006, pp. 260-265.
- [117] C.-H. Chang, P. Kourtessis, and J. M. Senior, "GPON service level agreement based dynamic bandwidth assignment protocol," *Journal of Electronics Letters*, vol. 42, pp. 1173-1174, 2006.
- [118] K.-M. Choi, S.-M. Lee, M.-H. Kim, and C.-H. Lee, "An Efficient Evolution Method From TDM-PON to Next-Generation PON," *IEEE Photonics Technology Letters*, vol. 19, pp. 647-649, 2007.
- [119] C.-H. Lee and K.-M. Choi, "Fiber to the Home," presented at The 20th Annual Meeting of the IEEE Lasers and Electro-Optics Society, LEOS 2007., Lake Buena Vista, Florida, 2007.
- [120] K. Iwatsuki, J.-i. Kani, H. Suzuki, and M. Fujiwara, "Access and metro networks based on WDM technologies," *Journal of IEEE Lightwave Technology*, vol. 22, pp. 2623-2630, 2004.
- [121] W.-K. Park, S.-I. Nam, C.-S. Choi, Y.-K. Jeong, and K.-R. Park, "An implementation of FTTH based home gateway supporting various services," *IEEE Transactions on Consumer Electronics*, vol. 52, pp. 110-115, 2006.
- [122] C. M. Assi, Y. Ye, S. Dixit, and M. A. Ali, "Dynamic bandwidth allocation for quality-of-service over Ethernet PONs," *Selected Areas in Communications, IEEE Journal on*, vol. 21, pp. 1467-1477, 2003.
- [123] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss, *An Architecture for Differentiated Services: IETF, RFC 2475*, Dec. 1998.
- [124] H. C. Leligou, C. Linardakis, K. Kanonakis, J. D. Angelopoulos, and T. Orphanoudakis, "Efficient medium arbitration of FSAN-compliant GPONs," *International Journal of Communication Systems*, vol. 19, pp. 603-617, 2006.
- [125] W. Lee, M. Y. Park, S. H. Cho, J. Lee, C. Kim, G. Jeong, and B. W. Kim, "Bidirectional WDM-PON based on gain-saturated reflective semiconductor optical amplifiers," *IEEE Photonics Technology Letters*, vol. 17, pp. 2460-2462, 2005.
- [126] C. Bock, J. Prat, and S. D. Walker, "Hybrid WDM/TDM PON Using the AWG FSR and Featuring Centralized Light Generation and Dynamic

- Bandwidth Allocation," *Journal of Lightwave Technology*, vol. 23, pp. 3981 - 3988, 2005.
- [127] D. P. Shea and J. E. Mitchell, "Operating Penalties in Single-Fiber Operation 10-Gb/s, 1024-Way Split, 110-km Long-Reach Optical Access Networks," *IEEE Photonics Technology Letters*, vol. 18, pp. 2463-2465, 2006.
- [128] S.-M. Lee, S.-G. Mun, and C.-H. Lee, "Consolidation of a metro network into an access network based on long-reach DWDM-PON," *Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference*, 2006.
- [129] D. Nessel, R. P. Davey, D. Shea, P. Kirkpatrick, S. Q. Shang, M. Lobel, and B. Christensen, "10 Gbit/s bidirectional transmission in 1024-way split, 110 km reach, PON system using commercial transceiver modules, super FEC and EDC," presented at European Conference on Optical Communication (ECOC), 2005, Glasgow, UK., 2005.
- [130] S. Hornung, D. Payne, and R. Davey, "New architecture for an all optical network," *presented at the conference of Optical Fiber Communication (OFC), Anaheim, CA*, vol. 2, 2005.
- [131] S.-M. Lee, S.-G. Mun, M.-H. Kim, and C.-H. Lee, "Demonstration of a Long-Reach DWDM-PON for Consolidation of Metro and Access Networks," *Journal of IEEE Lightwave Technology*, vol. 25, pp. 271-276, 2007.
- [132] F. Payoux, P. Chancelou, T. Soret, N. Genay, and R. Brenot, "Demonstration of a RSOA-based wavelength remodulation scheme in 1.25 Gbit/s bidirectional hybrid WDM-TDM PON," in *The Optical Fiber Communication Conference & Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*. Anaheim, California, USA, 2006.
- [133] J. Segarra, V. Sales, and J. Prat, "Traffic Performance of an Access Hybrid WDM/TDM PON with Colorless Reflective-ONUs under Different Distances OLT-ONUs," presented at 9th International Conference on Transparent Optical Networks (ICTON) 2007, Rome, Italy, 2007.
- [134] D. Nessel, M. Scopes, R. Davey, D. Shea, P. Healey, A. Borghesani, D. Moodie, A. Poustie, and R. Wyatt, "Demonstration of 100 km reach amplified PONs with upstream bit-rates of 2.5 Gb/s and 10 Gb/s," *presented at the european conference and exhibition on optical communication (ECOC), Stockholm, Sweden*, 2004.
- [135] G. Talli and P. D. Townsend, "Feasibility demonstration of 100 km reach DWDM superPON with upstream bit rates of 2.5 Gb/s and 10 Gb/s," *Presented at the conference of Optical Fiber Communication (OFC), Anaheim, CA*, 2005.
- [136] OPNET Modeler Version 10.0 Manual.
- [137] S.-i. Choi, "Cyclic Polling-Based Dynamic Bandwidth Allocation for Differentiated Classes of Service in Ethernet Passive Optical Networks," *Photonic Network Communications*, vol. 7, pp. 87-96, 2004.
- [138] G. Kramer and B. Mukherjee, "Interleaved Polling with Adaptive Cycle Time (IPACT): Protocol Design and Performance Analysis," *Technical Report. department of computer science, university of California*, 2001.

- [139] S. Lallukka and P. Raatikainen, "Link utilization and comparison of EPON and GPON access network cost," in *Global Telecommunications Conference (GLOBECOM) IEEE*, vol. 1. St. Louis, Missouri, US, 2005, pp. 301 - 305.
- [140] NTT, "NTT VDSL service plan," <http://www.asist.co.jp/jensspinnet/bflets.html>; Feb 2006.
- [141] W. Willinger, M. S. Taqqu, R. Sherman, and D. V. Wilson, "Self-similarity through high-variability: statistical analysis of Ethernet LAN traffic at the source level," *IEEE/ACM Transactions on Networking*, vol. 5, pp. 71-86, 1997.
- [142] K.-H. Ahn, K.-E. Han, and Y.-C. Kim, "Hierarchical Dynamic Bandwidth Allocation Algorithm for Multimedia Services over Ethernet PONs," *Journal of ETRI*, vol. 26, pp. 321-331, 2004.
- [143] Y. Shachaf, P. Kourtessis, and J. M. Senior, "An interoperable access network based on CWDM-routed PONs," presented at 33rd European Conference and Exhibition on Optical Communication (ECOC), Berlin, Germany, 2007.
- [144] P. Kourtessis, Y. Shachaf, C.-H. Chang, and J. M. Senior, "PON Topologies for Dynamic Optical Access Networks," presented at 10th International Conference on Transparent Optical Networks (ICTON), Athens, Greece, 2008.
- [145] T. Nakanishi, Y. Fukada, K.-I. Suzuki, N. Yoshimoto, M. Nakamura, K. Kato, K. Nishimura, Y. Ohtomo, and M. Tsubokawa, "Wide Dynamic Range and High Sensitivity APD Burst Receiver Configuration based on M-Switching Technique for 10GEPON System," presented at The 20th Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS), Lake Buena Vista, FL, USA, 2007.
- [146] S. Sari, B. Kalantari-Sabet, J. C. Attard, and J. E. Mitchell, "Radio over fibre networks," presented at Second International Conference on Access Networks & Workshops, (AccessNets), Ottawa, ON, Canada, 2007.
- [147] M. Sauer, A. Kobayakov, and J. George, "Radio Over Fiber for Picocellular Network Architectures," *Journal of IEEE Lightwave Technology*, vol. 25, pp. 3301-3320, 2007.
- [148] C.-T. Lin, J. Chen, P.-C. Peng, C.-F. Peng, W.-R. Peng, B.-S. Chiou, and S. Chi, "Hybrid Optical Access Network Integrating Fiber-to-the-Home and Radio-Over-Fiber Systems," *IEEE Photonics Technology Letters*, vol. 19, pp. 610-612, 2007.
- [149] T. Kuri, J. J. V. Olmos, and K.-i. Kitayama, "Photonic Dynamic Channel Allocation in Optical-Frequency-Interleaved DWDM Millimeter-Wave-Band Radio-over-Fiber Access Network," presented at IEEE International Topical Meeting on Microwave Photonics, Victoria, BC Canada, 2007.
- [150] J. J. Vegas Olmos, T. Kuri, and K. Kitayama, "Dynamic Reconfigurable WDM 60-GHz Millimeter-Waveband Radio-Over-Fiber Access Network: Architectural Considerations and Experiment," *Journal of IEEE Lightwave Technology*, vol. 25, pp. 3374-3380, 2007.
- [151] J. Yu, Z. Jia, T. Wang, and G.-K. Chang, "A Novel Radio-Over-Fiber Configuration Using Optical Phase Modulator to Generate an Optical mm-

-
- Wave and Centralized Lightwave for Uplink Connection," *IEEE Photonics Technology Letters*, vol. 19, pp. 140-142, 2007.
- [152] J. Jiang, M. R. Handley, and J. M. Senior, "Dynamic bandwidth assignment MAC protocol for differentiated services over GPON," *IET Electronics Letters*, vol. 42, pp. 653-655, 2006.
- [153] D. Verhulst, Y. Yi, X. Z. Qiu, S. Verschuere, Z. Lou, P. Ossieur, J. Bauwelinck, X. Yin, J. Vandewege, and B. De Vos, "Upstream experiments on the gigabit PON physical medium layer," in *Optical Fiber Communication Conference & Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, vol. 5. Anaheim, California, 2005.
- [154] ITU-T Recommendation G.7041, "Generic framing procedure (GFP)," 2001.
- [155] M. Nakamura, H. Ueda, S. Makino, T. Yokotani, and K. Oshima, "Proposal of Networking by PON Technologies for Full and Ethernet Services in FTTx," *Journal of Lightwave Technology*, vol. 22, pp. 2631-2640, 2004.
- [156] J. Jiang, M. R. Handley, and J. M. Senior, "GPON dynamic MAC protocol to support differentiated services," presented at The 2nd Institution of Engineering and Technology International Conference on Access Technologies, Cambridge, UK., 2006.
- [157] T. Tsutomu, Y. Yukihiro, and M. Yoichi, "Standardization of G-PON (Gigabit Passive Optical Network) in ITU-T," *NTT Technical Review*, vol. 1, pp. 89-93, 2003.
- [158] ITU-T Recommendation I.432, "B-ISDN UNI Physical layer specification," 1993.

Appendix A

Frame formats of GPON packet, dynamic bandwidth report upstream and upstream bandwidth maps

Figure A-1 presents the downstream frame structure of GPON. It is set to 125 μ s including the PCBd (Physical Control Block downstream) and the payload [3, 28, 31, 152]. In the network, the PCBd is filled by control field and upstream bandwidth maps (US BW Maps). to control the physical connections, such as physical synchronisation and physical layer operations, administration and management (PLOAM) [31, 83], and to comprise the information of upstream transmission time-slots, such as upstream start/stop times, for N ONUs respectively.

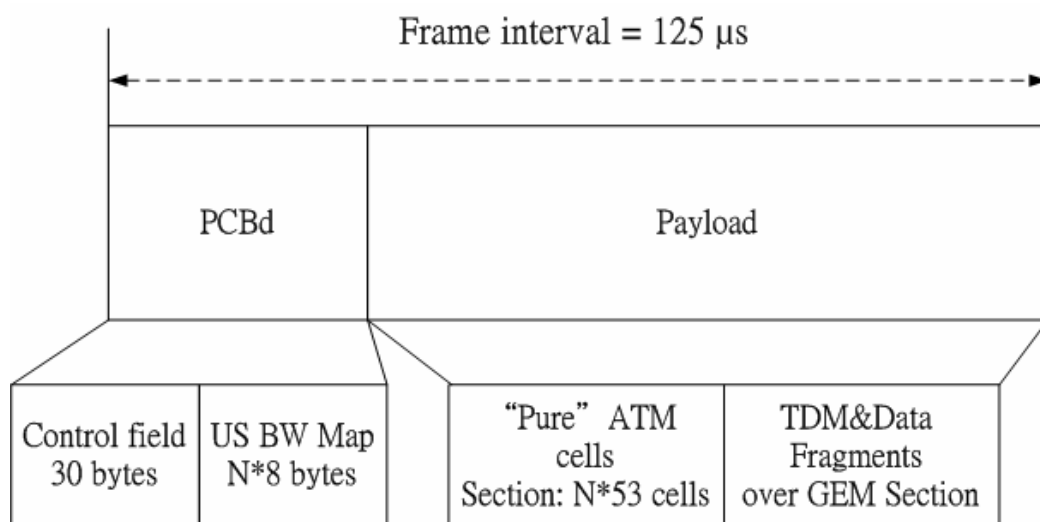


Figure A-1 GPON downstream frame formats [139]

To look closer to the upstream bandwidth maps, the field is a scalar array of 8 bytes map structures as presented in Figure A-2. Each map includes the following information:

- The allocation ID (12 bits): Indicating an ID for an ONU. In GPON, each ONU can be assigned with multiple allocation IDs (0-255) corresponding to different logical links for various multimedia service applications. The ID 0-253 is used for ONU ID directly. The 254 is activation ID used for discovering unknown ONUs and the 255 is reserved for broadcasting purpose.
- The flags (12 bits): Used by OLT to control ONU transmission of physical layer overheads, such as preamble, delimiter.
- The start time (2 bytes) and stop time (2 bytes): Indicates the start and stop time of upstream transmission window.
- The cyclic redundancy check (CRC) (1 byte): Used to detect one single bit error in a received message [153].

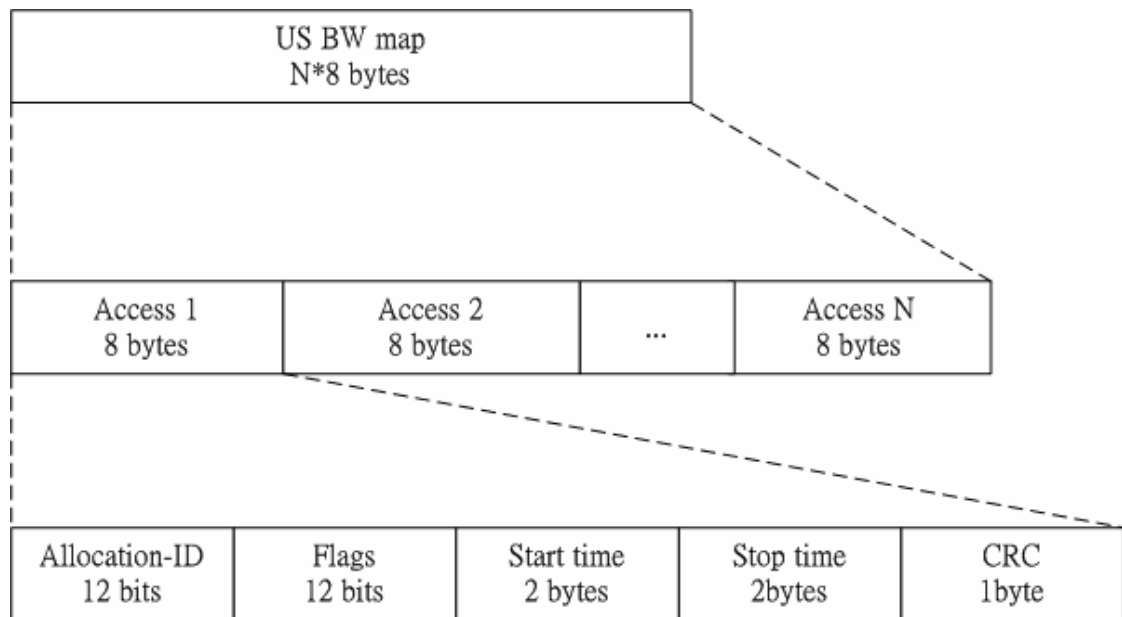


Figure A-2 GPON upstream bandwidth map

In addition to the PCBd, the payload in the GPON downstream frame includes the ATM section and GPON encapsulation method (GEM) section. The ATM section is used to transmit ATM cells, utilised in some network, such as APONs. The GEM section, specified based on ITU-T G.7041 [154], is employed to transmit GPON packets. By using GEM, diverse protocols signals, such as Ethernet or T1/E1 TDM system, can be encapsulated and fragmented into different GPON packets, conveniently allowing the network to match to the deployed network systems. Hence the GEM has become the preferred scheme for efficiently transmitting data [3, 28, 155-157], and the ATM will thus not be discussed further in this thesis.

In the GEM sections, each GPON packet is composed of a GEM header and either a frame fragment or full frame. The header is used to record and notify the receiver about the information of its relative payload, such as the payload length and type. In order to develop a suitable protocol for GPONs, this packet format is analysed in this thesis and is used to deliver data in the GPON simulation model. As shown in the Figure A-3, the GEM header includes the following five fields [28]:

- The PLI, payload length indicator (12 bits): Used to indicate the payload length.
- The Port ID (12 bits): Used for multiplexing of data flow.
- The PTI, payload type indicator (3 bits): Used to show payload type.
- The HEC, header error control (13 bits): Used to correct single bit error or detect multiple bit error.
- The Fragment Payload (L bytes): Used to record the optional information of fragment payload [28, 31, 158].

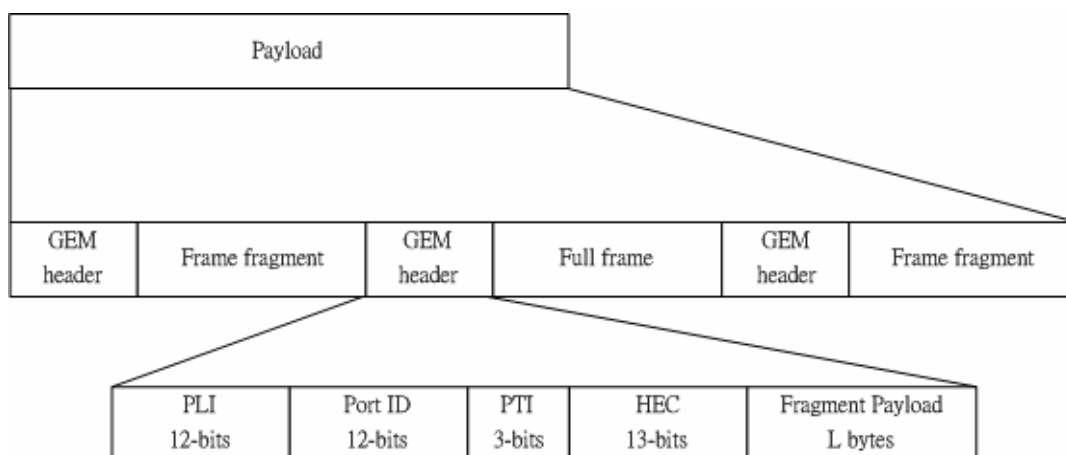


Figure A-3 GEM header

By receiving the GPON downstream frame, each ONU not only obtain its downstream data but also can acquire a permission to transmit its data. The ONU responds to permission by recording its buffer queuing status in a report message called the “Dynamic Bandwidth Report upstream” (DBRu). It then transmits to OLT at the beginning of the dedicated upstream time-slot. This optional 5 bytes packet is then utilised by the OLT to dynamically arrange the next upstream transmission.

Appendix B

Publications

Published papers:

C.-H. Chang, P. Kourtessis, and J. M. Senior, "Service level agreement based dynamic bandwidth allocation for GPONs," in 11th European Conference on Networks and Optical Communications (NOC). Berlin, Germany, 2006, pp. 260-265.

C.-H. Chang, P. Kourtessis, and J. M. Senior, "GPON service level agreement based dynamic bandwidth assignment protocol," *Journal of Electronics Letters*, vol. 42, pp. 1173-1174, 2006.

C.-H. Chang, P. Kourtessis, and J. M. Senior, "Dynamic Bandwidth assignment for Multi-service access in GPON," presented at 12th European Conference on Networks and Optical Communications (NOC). Stockholm, Sweden, 2007.

Y. Shachaf, C.-H. Chang, P. Kourtessis, and J. M. Senior, "Multi-PON access network using a coarse AWG for smooth migration from TDM to WDM PON," *Journal of OPTICS EXPRESS*, vol. 15, pp. 7840-7844, 2007.

C.-H. Chang, N. M. Alvarez, P. Kourtessis, and J. M. Senior, "Dynamic Bandwidth assignment for Multi-service access in long-reach GPON," presented at 33rd European Conference and Exhibition on Optical Communication (ECOC), Berlin, Germany, 2007.

Gliwan, C.-H. Chang, Y. Shachaf, P. Kourtessis, and J. M. Senior, "Upstream Format Map Enhancements for Multi-Wavelength GPONs," presented at 13th

European Conference on Networks and Optical Communications (NOC), Krems, Austria, 2008

P. Kourtessis, Y. Shachaf, C.-H. Chang, and J. M. Senior, "PON Topologies for Dynamic Optical Access Networks (Invited)," presented at the 10th International Conference on Transparent Optical Networks (ICTON 2008), Athens, Greece, 2008.

Under review's papers:

C.-H. Chang, P. Kourtessis, and J. M. Senior, "Advanced Dynamic Bandwidth Assignment Protocol for Multi-service access in GPON," *Journal of IEEE Network*, 2007.

In preparation:

C.-H. Chang, N. M. Alvarez, P. Kourtessis, and J. M. Senior, "Two-state Bandwidth assignment for Multi-service access in long-reach GPON," *Journal of IEEE Lightwave Technology*, 2007.